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Contents

page

iii Editorial

iv Editor's notes to contributors

1 The Permo-Carboniferous magmatism of northern Britain: was this triggered by a mantle plume? (abstract)
Prof. Marjorie Wilson

3 Jurassic extinction from Yorkshire to Tibet (abstract)
Prof. Paul Wignall

5 Carboniferous geology of northern England
Dr Colin N. Waters

17 Dinosaur footprints on the Yorkshire coast
Dr Mike Romano

27 The Ebb and flow of the Yorkshire margins of the last British ice sheet (abstract)
Dr Mark D. Bateman

29 Palaeoclimate modeling: the past as a guide to the future (abstract)
Dr Alan M. Haywood

31 Enter the Anthropocene: an Epoch of time characterised by humans
Dr Mark Williams and Dr Jan Zalasiewicz

35 Volcano–ice interactions in Iceland (abstract)
Dr Dave McGarvie

37 Magma chamber evolution and large volcanic eruptions
Dr Dan Morgan

41 Summary: Did Yorkshire rock for you?
Chairman Linda Fowler

Book reviews are on pages 2, 4, 26, 28, 30 and 36

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Cover illustrations: Thin sections of several different habits of barite (photographs by Jane Clarke).

botryoidal barite mag. 538×; ppl	acicular barite mag. 549×; xpl	poikilotopic barite mag. 530×; xpl
bladed barite (white) mag. 580×; ppl	botryoidal barite mag. 538×; xpl	spherulitic barite mag. 584×; xpl
fasicular-optic barite mag. 549×; xpl	banded barite mag. 538×; xpl	banded barite mag. 538×; ppl

Editorial:

There were nine talks delivered at the OUGS Symposium 2009 in Leeds, plus the summing up by Chairman Linda Fowler at the end. Your Editor spoke to all nine speakers at the symposium about papers on their talks for the *OUGS Journal*, and diligently contacted the speakers repeatedly in the months after the Symposium. Each talk was recorded, and for those speakers who requested it a transcript was made by our volunteer transcribers.

Nevertheless, several speakers were unable to deliver a paper for publication in our journal.

It is with extreme regret and apologies that this issue of the *OUGSJ* is so late in publication. After months of contacting the speakers it was finally decided by the OUGS Committee to publish those papers received and to publish abstracts only of those not received.

At the OUGS Committee meeting at this year's AGM it was decided that we will no longer record and transcribe Symposium papers, and so will be reliant on speakers to submit papers.

As your Editor I thank all OUGS members for your extraordinary patience.

— David M. Jones, *OUGS Journal* Editor

Errata

As members will have realised last October, the 'Spring' Edition 30 (1) of the *OUGSJ* was anything but spring! There were many delays in getting final materials from the various sources. Please accept my apology for its lateness.

No doubt you all spotted, as I did the minute I opened my own copy, the error at the top of the contents page (ii): it should, of course, be 'Spring Edition 2009'

At least the details on the cover, title page and running heads are correct as Spring Edition 2009 Volume 30 (1).

I also missed a couple of errors on page 20: misspelled 'centaury' should be 'century', of course; and a square [ ] bracketed editorial query that I somehow forgot to delete — for which apologies to Kevin Brown. And, for this supposedly exacting editor, there is a 'c.' that should be in italic — see if you can spot it!

My only feeble excuse is that I was so concerned about the lateness that I missed these errors.

Since publication of the Spring Edition I have also learned that Gareth George's *The Geology of South Wales*, reviewed on page 18 by Rosemary Darby, is not in fact available from OUGS Sales. Copies can be ordered directly from the author at garethtgeorge@geoserve.co.uk

Editor's notes to contributors

Following are guidelines for the submission of articles to the *OUGS Journal*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Journal*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention (I will probably spot them anyway) so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Journal* articles

As *OUGS Journa*l Editor I do not want the publication of your paper to be more work than is necessary for you (or for me!). Your paper need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material.

Regarding papers from the presenters of lectures at the OUGS Symposium, all OUGS members are grateful to you for presenting a talk at the OUGS Annual Symposium, and for agreeing to submit a version of your talk for publication in the *Journal*. The purpose of this is to make your information available to OUGS members and others who could not attend the symposium. As OU students and OUGS members we enjoy hearing and learning the information these symposia bring to us.

All that is necessary is the following:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Journal* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your paper, it may be a good idea to send one with these items marked up or otherwise highlighted. Otherwise I can accept electronic files attached to an e-mail, or files on a CD.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 350dpi minimum for colour or half-tone images; 1400dpi for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 15. Obviously as a symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to include with the paper to be published — again usually 10 to 15 is a rough guide. *Please note that figures are normally printed in greyscale in the* OUGS Journal*, except Moyra Eldridge Photographic Competition winners' photographs.*

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.

As the author, this responsibility is yours.

• Please do not embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustration should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a web site), full title, periodical volume and number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you as necessary as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3 edn). Cambridge: Cambridge U. P.

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2 edn). Oxford: Oxford U. P.

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford U. P.

Please contact me at any time about your paper:

Dr David M. Jones, *OUGS Journal* Editor;
journal@ougs.org

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The Permo-Carboniferous magmatism of northern Britain: was this triggered by a mantle plume?

Prof. Marjorie Wilson (School of Earth and Environment, University of Leeds)

During Carboniferous and Permian times, northern Europe experienced widespread magmatism and graben formation, which was intimately related to the evolution of the Variscan orogenic belt to the south. The earliest manifestations of this activity are in the UK and Ireland. Magmatism was unevenly distributed; the main areas include the Oslo-Skagerrak Graben, Scania (southern Sweden), the Danish island of Bornholm, eastern Britain and the North Sea, and northern Germany (Fig. 1). In contrast to the long-lasting tectonic activity, magmatism in these areas was concentrated in a restricted period, starting *c.* 300Ma ago, with the bulk of the activity occurring between 300Ma and 280Ma (Fig. 2).

An important issue concerns the relative roles of far-field stresses versus dynamic upwelling of the upper mantle (i.e. one or more mantle plumes) in the initiation of the Permo-Carboniferous rift system of northern Europe, and in the petrogenesis of the associated magmas. Magmatism and regional tectonics are intimately linked, and heterogeneities in lithospheric thickness appear to play an important role in localising the sites of decompression partial melting.

The majority of the most primitive Permo-Carboniferous lavas in the Oslo rift, southern Scotland, northern England and parts of Ireland appear to be small-degree partial melts of one or more sub-lithospheric mantle sources. The rising mantle-derived magmas, however, have often been modified subsequently by shallow-level processes. These include magmatic differentiation and lithospheric contamination (both crust and mantle), which mask the geochemical signatures of the mantle sources. The enriched asthenospheric mantle source of the most primitive magmas in many areas bears some similarity to the source of modern-day Hawaiian and Icelandic basalts, which are generally assumed to be plume-related. However, while the limited He isotope data available for basalts from Scotland could be considered consistent with the involvement of low $^{3}He/^{4}He$ mantle plume — similar to the source of present-day HIMU (High-m) ocean island basalts — in the petrogenesis of the magmas it seems much more likely that magma generation was a complex response to far-field stresses and to the tectonic collapse of the Variscan orogen.

Geochemical and structural studies of regional dyke swarms in Scotland, Norway and Sweden suggest that there were at least five different intrusive events. One of the most extensive is the widespread emplacement of tholeiitic dykes and sills over a short time interval close to the Carboniferous-Permian boundary *(c.* 300Ma). These intrusions (which include the Whin Sill) appear to reflect a short-lived, high-degree melting event over a wide region, which may have been tectonically induced by wrench faulting.

Reference

Wilson, M., Neuman, E.-R., Davies, G. R., Timmerman, M. J., Heeremans, M. and Larsen, B. T. (eds) 2004 P*ermo-Carboniferous Magmatism and Rifting in Europe*. London: Geol Soc Special Publ **223**

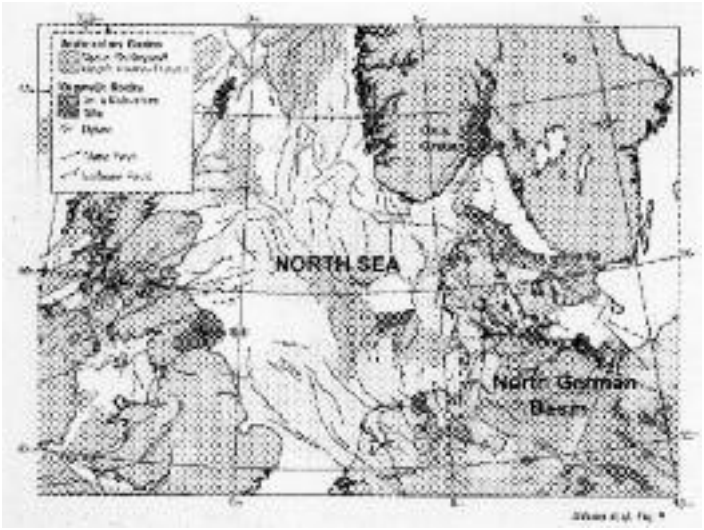

Figure 1 Map of the Permo-Carboniferous magmatic province of northern Europe.

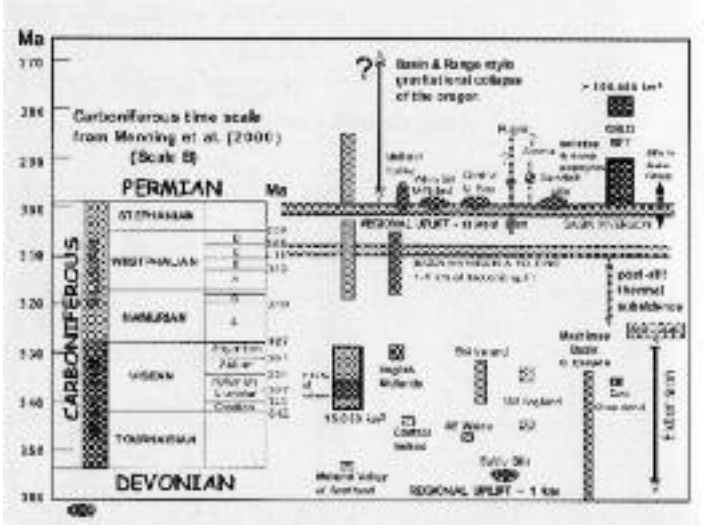

Figure 2 Timing of Permo-Carboniferous rifting and magmatism in northern Europe.

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Book review

Edwards, Stephen, Hudson-Edwards, Karen, Cann, Joe, Malpas, John and Xenophontas, Costas 2010 *Cyprus*. Harpenden: Terra Publishing (ISBN 978-1-903544-15-0; paperback, x + 271 pp; £17.95).

Readers of the *OUGS Journal* who visit Cyprus mostly geologise as part of an organised field trip; those (like me) who have tried to work it out without benefit of a leader have hitherto used the *Geologists' Association Guide 50: Southern Cyprus* by Greensmith. I have found Greensmith's most helpful and easy to use; I cannot compare it directly with this new work (part of enterprising Terra Publishing's new 'Classic Geology in Europe' series), because I left my Greensmith with my Cyprus hosts, who appear to have lost it between my next visits.

Edwards *et al.* is considerably longer, and not much more expensive. Like Greensmith, Edwards *et al.* omit northern (Turkish) Cyprus; there is precisely one page on the important Kyrenia Terrane, despite its "long and complex history… [containing] the oldest rocks in Cyprus", and, uniquely for the island, having "structures reminiscent of a small Alpine-type fold and thrust belt". With increased access to the north from the south, this omission of any detailed field guides to the Kyrenia terrane seems to me a misjudgement.

This omission apart, Edwards *et al.* is an excellent work. It is written for the "well informed amateur and undergraduate geologist" and uses a logical "thematic approach". There is an introductory chapter dealing not only with the island's geological history but also with its landscape, topography, climate and meteorology, soils and agriculture, fauna and flora, and human history. There are then three chapters on the island's chief claim to geological fame: the Troodos ophiolite. Troodos is the type-example of all ophiolites, and Edwards *et al.* deal with it in three parts: the lower section (mantle and plutonic sequences), the upper section (sheeted dyke and volcanic sequences, and sulphide and umber), and the complex faulting.

Each of these themes includes field stops "described in a stand-alone fashion", as do other chapters on the Mamonia terrane, the circum-Troodos sedimentary succession, and "resources, wastes and hazards". A final chapter describes how the more significant of these stops can be combined in nine day-long itineraries.

Interesting non-geological themes are also brought in, for example Lefkara's lace and silver (not so thriving as the text implies) and the Neolithic site at Choirokoitia.

There are seven pages of glossary, ten of useful contacts and publications, and an index of localities and a subject index. The maps, figures and photographs are all in black and white, which has no doubt kept the price reasonable, but at the expense of the fullest benefit from the photographs. Standard government names are used: Nicosia is referred to throughout as Lefkosia, Limassol as Lemesol.

— Philip Clark, MA, BSc Hons (Open), Dip Mus (Open)

Book review

Lewis, C. L. E. and Knell, S. J. (eds) 2009 *The Making of the Geological Society of London*. London: Geological Society Special Publ 317 (ISBN 978-1-862392-77-9; hardback, xi + 471pp; £120)

The excellent lectures at our Egham symposium showed the wealth of interest that there is in the history of geology, and in particular revealed the many strands of social, cultural and intellectual life that this history involves and illuminates. This magnificent volume of essays, most given as talks at the Geological Society's bicentenary celebrations in 2007, deepens the impression that we are fortunate to live in an age of highly sophisticated historiography. The roles of medical men, military men, Dissenters (particularly Quakers) and chemists in the early days of our science are brought forward alongside many important affairs in the background: the campaign for the abolition of slavery, the reforms in hospitals and the organisation of the medical profession, the disparity in incomes across the social spectrum — all of them significant to the advancement of geology when seen from the right angle.

Certain essays — particularly those of Simon Knell ('The road to Smith: how the Geological Society came to possess English geology'), of Martin Rudwick ('The early Geological Society in its international context') and of Ralph O'Connor ('Facts and fancies: the Geological Society of London and the wider public, 1807–1837') — are extremely illuminating in showing how the enterprise of geology came to be established in the form we know it in the half century between 1790 and 1840. The balance between the collection of facts and theorising from these facts, the international nature of the enterprise, the contribution of professionals and amateurs (amateurs, lovers of the science, not ignoramuses!), the establishment in the popular mind of the romance and excitement of the quest, all these are recognisable features of today's geological scene, and this is how they arose.

The story overseas, in France, the leading scientific nation in 1807, in Italy, Germany, Russia, the United States, and later in the Antipodes, is dealt with in detail. An appendix gives the fascinating *Geological Enquiries* of 1808, the first mission undertaken by the new society.

It cannot be said that this volume is as readable as the Geological Society's other contribution to their bicentenary, Gordon Herries Davies's *Whatever is Under the Earth* (reviewed in the *OUGS Journal* Spring edition 2008 Vol. 29 No. 1, 27). Nor is it as physically attractive a volume, with its double columns and the small typeface used, which becomes minuscule for the abstracts and for lengthy quotations printed as separate paragraphs. But it goes into much detail behind Herries's first two or three chapters, and is frequently as amusing or caustic.

The volume is profusely illustrated, well indexed, and has extensive bibliographies for each chapter.

In this reviewer's opinion, it is a sad commentary on current OU provision for study that the only course in 'History of Science, Technology and Medicine' is 'Medicine and society in Europe 1500–1930' (A218).

— Philip Clark, MA, BSc Hons (Open), Dip Mus (Open)

Jurassic extinction from Yorkshire to Tibet

Prof. Paul Wignall (School of Earth and Environment, University of Leeds)

The Toarcian Stage of the Early Jurassic marks one of the most significant extinction events in the reign of the dinosaurs, although it is not of comparable magnitude to the great end-Permian or K-T mass extinctions. The Yorkshire coast provides one of the best marine sections through this Toarcian interval. The key sections are found above the Cleveland Ironstone Formation in outcrops that stretch from Staithes in the north to Robin Hood's Bay in the south. The stratigraphy consists of the Grey Shales — a descriptively named rock unit — overlain by the Jet Rock that is named for the rare pieces of fossil driftwood that occur within it.

The first hint that there were problems in the Jurassic seas is the abrupt change in the composition of the ammonite faunas between the Cleveland Ironstone and the Grey Shales. Thus, coarsely ribbed *Pleuroceras* species are replaced by either finely ribbed *Dactylioceras* species or the streamlined *Harpoceras* ammonites. Like many similar turnover events in the history of the ammonites, this example coincides with a sharp regression or sea level fall that preceded a subsequent transgression or sea level rise in the Grey Shales.

The ammonites were free-swimming creatures that probably lived in the water column, but the next crisis to affect the Jurassic marine life struck the creatures that lived on the sea floor, especially bivalves and gastropods. This occurred towards the top of the Grey Shales and is a much more unusual event in Jurassic history because these sea-floor denizens generally lived long, unspectacular lives with only the occasional species disappearing. The abrupt loss of most bivalve species late in Grey Shale deposition required unusual circumstances and these are recorded by the rocks at this level: they change from structureless mudstones to finely laminated shales with abundant tiny crystals of pyrite. This evidence suggests the loss of oxygen in the bottom waters (anoxia), and provides a clear reason for the extinction. The fact that this same transition is widespread in NW European sections is further reason for thinking that it is a significant change.

Typically in the geological record, anoxic seafloor conditions are associated with transgression, but this is not the case with the Grey Shale example because there is evidence for slight sea shallowing at the start of the anoxia. Thus, thin storm-beds and wave-rippled fine sands are seen in the Grey Shales at this level, pointing to a shallowing to within the reach of storm wave influence — perhaps 50–100m water depth in this Jurassic basin. Much deeper water conditions (and the persistence of anoxia) are seen in the overlying Jet Rock, although even in this unit weak evidence for storms is seen in the form of erosive gutters in-filled with shells and erosive scours.

So how does the Early Jurassic story from England compare with that from southern Tibet? In the Early Jurassic this part of the world was in the southern hemisphere, around 30º south, and lay on the northern margin of the Gondwana continent, which itself was part of the supercontinent of Pangea. Sea depths were generally shallower than those seen in Yorkshire and carbonate sediment was accumulating. This primarily consisted of microfossils called foraminifera, larger fossils such as large aberrant bivalves called lithiotids and a lot of little oval grains called peloids. The lithiotids are characteristic Early Jurassic fossils and provide a handle on the age of the rocks. However, to provide a better time resolution within this interval, palaeontologists usually rely on ammonites. But these do not occur in the Tibetan sections.

An alternative fossil group used in age dating Jurassic limestones are the tiniest of all fossils: calcareous nannoplankton. The search for these in the Tibetan limestones has proved rather tricky, but a few examples have turned up and they give a rough idea of where the top of the Toarcian Stage occurs. Intriguingly, this level also seems to coincide with the extinction event in this region — the lithiotids are the most obvious victims in Tibet. This is significantly later than the time of extinction in Yorkshire, where the bivalve losses occurred in the early part of this stage. This suggests that the crisis was not globally synchronous.

So, what happens at the moment of extinction in Tibet? Here the comparison with Yorkshire is closer: darker, more pyritic limestones occur above the level where the last lithiotids disappear, suggesting that oxygen-poor waters may have caused the demise. Truly anoxic conditions like those encountered during Jet Rock deposition are not seen in Tibet, but rather a more dysoxic (oxygen-poor) environment seems to have developed.

The fact that the Toarcian extinction is not strictly synchronous in Yorkshire and Tibet may go someway to explaining why this was only a minor extinction crisis and not a mass extinction, because the truly catastrophic events, such as that at the end of the Permian, saw awful conditions simultaneously all over the world. There was nowhere to hide during these crises. In contrast, this Early Jurassic event saw the region-by-region demise of certain groups.

So, what was the driver of these changes? One clue comes from the changes in the carbon isotope ratios recorded in both organic matter and limestone. This is recorded by the ratio $^{13}C/^{12}C$: any changes in this ratio reflect relative changes in the carbon found in the Jurassic ocean-atmosphere system. During the Toarcian there is a big change to lower ratios (^{12}C becomes relatively more abundant than ^{13}C), although the nature of this change is highly controversial because it is well seen in organic matter but not very clearly seen in some limestones.

Assuming it is true change, there are several potential causes. One cause, and a popular one with some geologists, is the release of methane into the atmosphere from deep-sea clathrates (methane-ice structures found beneath the sea bed). The impact of such an event would be to cause global warming and thus provide at least the beginnings of a potential kill mechanism. Alternatively, volcanoes can release carbon dioxide that also causes the atmospheric $^{13}C/^{12}C$ ratio to decrease, although it would require a huge amount of volcanism to achieve this.

As it happens we know there was a lot of volcanic activity occurring at this time in South Africa and in Antarctica. This is known as the Karoo-Ferrar flood basalt province and involved the eruption of several million cubic kilometres of lava. There are strong parallels between these events and those seen during many other extinction events — nearly all of them coincide with flood basalt eruptions. However, the problem with all of them is evaluating the causal link between the eruptions and events seen in the ocean, such as the oxygen-deficiency seen during the Toarcian. Ultimately, we need to understand the interactions within the Earth system to fully comprehend such mass extinction crises.

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Book review

Kearey, Philip, Klepeis, Keith A. and Vine, Frederick J. 2009 *Global Tectonics* (3 edn). Oxford: John Wiley & Sons (Wiley-Blackwell) (ISBN 978-1-405107-77-8; paperback, 496pp; £34.99, €40.30)

The second edition of Kearey's *Global Tectonics*, with Vine as co-author, appeared in 1996 and ran to 333pp. So this third edition, written by Vine and Klepeis after Kearey's early death, is considerably expanded, and as the authors say, "two-thirds of the figures and two-thirds of the text… are new". The figures, incidentally, are excellent; they are in black and white, apart from 16 colour plates in the middle of the book, but are extremely clear and easy to read. Most are from other publications, but have been redrawn so that they feel uniform, which is always helpful.

Vine, Emeritus Professor at the University of East Anglia, is a veteran of plate tectonics, a Fellow of the Royal Society for his work on the interpretation of oceanic magnetic anomalies and ophiolites; Klepeis is a Professor of Geology at the University of Vermont, and specialises in the areas of structural geology and continental tectonics, and has worked extensively on the evolution of orogenic belts and fault systems in New Zealand, Patagonia, West Antarctica, Australia, British Columbia and south-east Alaska. They have kept the logical outline of earlier editions, which makes the work easy to follow, indeed a pleasure to use as a revision read: 1 Historical perspective, 2 The interior of the Earth, 3 Continental drift, 4 Seafloor spreading and transform faults, 5 The framework of plate tectonics, 6 Ocean ridges, 7 Continental rifts and rifted margins, 8 Continental transforms and strike-slip faults, 9 Subduction zones, 10 Orogenic belts, 11 and 13 new and expanded chapters on Precambrian tectonics and the supercontinent cycle, and on the implications of plate tectonics for environmental change, economic geology and natural hazards, and 12 The mechanism of plate tectonics.

Perhaps because of the areas where the authors have worked, there is very little on British, or indeed on European tectonics. There are welcome recaps of areas visited in S339: the Himalayas/Tibet, the Red Sea/Kenya, the Andes, and interesting detail on areas probably new to most of us, such as the north of Western Australia, the Woodlark Basin between Papua New Guinea and the Solomons, and Japan. New Zealand, where almost all of our members seem to be fetching up these days, is well covered.

There are 35 pages of references, 50 'Review questions', an excellent index, and a dedicated website available at www.blackwellpublishing.com/kearey/, where all the figures in the text download fairly easily, either in high or low resolution.

— Philip Clark, MA, BSc Hons (Open), Dip Mus (Open)

Book review

Violante, C. (ed) 2009 *Geohazard in Rocky Coastal Areas*. London: The Geological Society Special Publication 322 (ISBN 978-1-862392-82-3; hardback; £80)

The Geological Society of London has a commanding place in present-day geological publishing. Its 'special publications' are a natural place to publish monographs and especially collections of papers on particular topics. This collection also witnesses to the commanding position in the geological world of the native language of the Geological Society of London, for the rocky coastal areas of which it treats are almost exclusively those of Italy, and all the 30 or so authors (apart from one Hungarian) are Italians — writing in excellent English.

The editor works at the Institute for Coastal Marine Environment in Naples, and six of the eight co-authored papers deal with the neighbourhood of Naples: Capri, Ischia, the Sorrento Peninsula, especially Amalfi, and the long-term effects on those coasts of debris from eruptions of Vesuvius. One chapter is about eastern Liguria, another surveys 2850km of Italian coastline (out of a total of 8100km) that comprises "steep-sloping, mostly rocky, cliffs or bluffs directly plunging into the sea, or separated from it by a thin strip of sandy or gravel beach or a reef of fallen blocks". The authors of that chapter point out that before the extensive land reclamation works of the 19th and 20th centuries there were many more rocky Italian coasts.

The introductory chapter by the editor on "Rocky Coast: geological constraints for hazard assessment" refers to other areas such as "the open-ocean coastlines bordering the Pacific Ocean, the peninsular Gulf of California margin and the Gulf of Corinth in Greece", South American coastal ranges, New England coastal bluffs, Hokkaido, Papua New Guinea and so on. But even this chapter is illustrated in detail by the eastern Tyrrhenian Sea, down to the example of the value of historical documents to "enhance the reconstruction and knowledge of the occurrence of geohazards in a given coastal area". (A page of beautiful Italic handwriting is reproduced showing reimbursement for repairs to paper factories following a flood in 1736.)

Anyone considering SXG390, the geohazards project course, would find in this collection many useful ideas towards a topic. "Geological hazard along rocky coasts is basically associated with processes of rapid sediment transfers. Massive transport of rock, regolith, sedimentary cover and soil occur episodically, accounting for cliff recession, sudden increase in solid load in short coastal rivers, and flank collapse of volcanic structures and rocky slopes".

Anyone else, particularly those who frequent the rocky coasts of Britain, will find this a fascinating volume to dip into. Incidentally, Britain and its principal islands have a coastline of more than 31,000km, a substantial amount of which is rocky, so you do not have to go far for these geohazards.

— Philip Clark, MA, BSc Hons (Open), Dip Mus (Open)

Carboniferous geology of northern England

Dr Colin N. Waters (British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham)

Abstract

The British Geological Survey (BGS) has produced a wholesale rationalisation of Carboniferous lithostratigraphical nomenclature. This presentation describes the Carboniferous stratigraphy of northern England, illustrated with research carried out as part of recent BGS mapping projects.

During the Tournaisian and Visean a phase of north–south rifting resulted in the development of grabens and half-grabens, separated by platforms and tilt-block highs. Visean marine transgressions resulted in the establishment of platform carbonates, which gradually onlapped raised horst and tilt-block highs. The evolution of one such tilt-block high, the Askrigg Block, and associated Great Scar Limestone Group, is described in detail. During late Visean times a cyclic succession of fluvio-deltaic clastics, marine reworked sandstones and shallow-shelf marine carbonates (Yoredale Group) dominated across northern England, terminating deposition of the platform carbonates. To the south of the Craven fault system, which defines the southern margin of the Askrigg Block, the block and basin structures persisted, though generally the high subsidence rates created a province dominated by hemipelagic mudstones and carbonate/siliciclastic turbidites (Craven Group).

Cessation of rifting during the late Visean in the area between the Southern Uplands and the Wales–Brabant High resulted in a period dominated by thermally induced regional subsidence during Namurian and Westphalian times, with formation of the Pennine Basin. During early Namurian times fluvio-deltaic systems started to feed siliciclastic sediment into the northern margin of the basin (Millstone Grit Group). Initial deposition in the basinal areas is marked by the formation of thick turbidity-fronted delta successions. By late Namurian times, the southern part of the basin began to be infilled by fluvio-deltaic systems entering the basin from the east and south-east, but ultimately still sourced from the north. Three case studies are described in detail: the Kinderscout Grit, Ashover Grit and Chatsworth Grit. The development of these sand bodies occurred within a regime of regular and marked sea level changes. Evidence will be provided for the duration of this cyclicity.

From early in the Westphalian, a coal-forming delta-top environment, associated with formation of the Pennine Coal Measures Group became established across the Pennine Basin. There was gradual waning of the influence of marine flooding events in the basin. The sediment influx into the Pennine Basin progressively changed from a dominantly northern provenance, comparable to the Millstone Grit Group, to initially a western source and subsequently to a southern one, later in the Westphalian.

Introduction

The Carboniferous, arguably more than any other system, is emblematic of the geology of northern England, and of Yorkshire in particular. The mineral resources present within Carboniferous strata were of paramount importance in the development of the Industrial Revolution in Britain and controlled the location and growth of some of our northern cities, including Leeds, the home of this year's OUGS Symposium. If one considers the archetypal landscape of northern England it is likely to include the wild moors of the Pennines, or the grand scenery of the Yorkshire Dales. These areas have been the focus of much research over the decades and still offer new discoveries, some of which will be described in this paper.

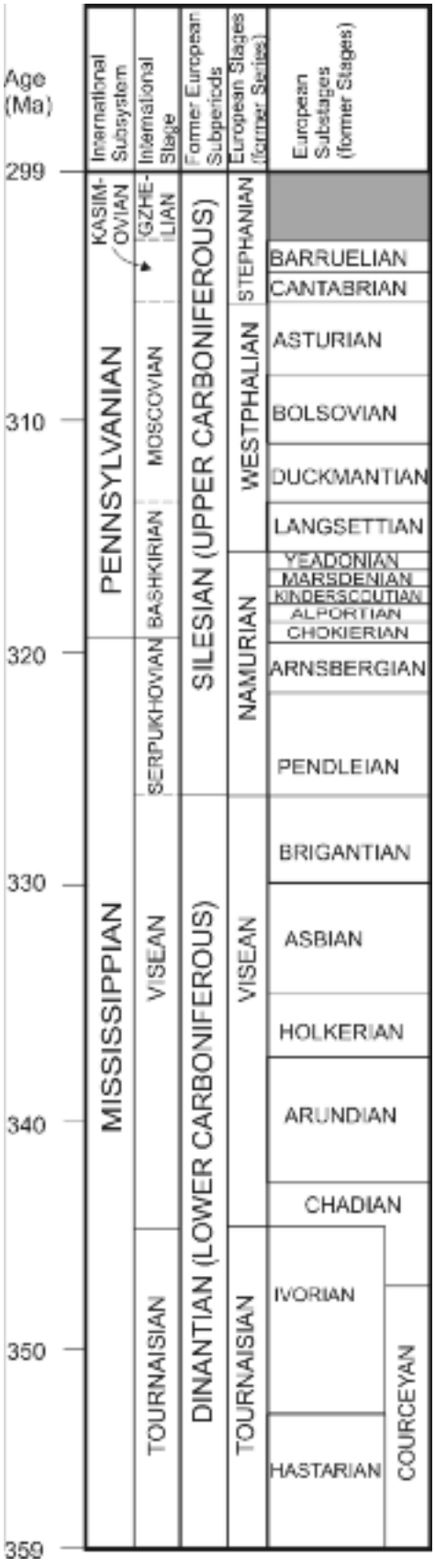

Figure 1 (right) Carboniferous chronostratigraphical nomenclature (redrawn extract from Waters (ed and comp) 2008).

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This paper describes: recent changes to the chronostratigraphical nomenclature used to subdivide the Carboniferous Period; the plate tectonic setting relevant to the story of the sedimentary evolution of the Carboniferous of northern England; a new lithostratigraphical scheme, developed recently by the BGS to rationalise the multitude of local terminologies and to better reflect the evolution of depositional environments with time; and a systematic description of the Carboniferous succession of northern England.

Chronostratigraphy

The international chronostratigraphical nomenclature for the Carboniferous comprises two subsystems, the Mississippian and Pennsylvanian (Fig. 1, *previous page*), with the familiar Dinantian and Silesian — now obsolete terms. The International Committee on Stratigraphy has introduced six unnamed series, which are largely one-to-one matches with the new international stages. The early Carboniferous stages of Tournaisian and Visean have been used in the UK for several decades. Younger international stage names are less familiar, mostly derived from key Russian sections. However, in the UK we have long-established terms that are still acceptable to use, though now downgraded. The Namurian, Westphalian and Stephanian have become regional stages, where they used to be series, and stages such as Courceyan, Chadian etc. have been downgraded to regional substages. Because Figure 1 is scaled with reference to time, it shows how short the durations of some of these substages were within the Pennsylvanian, which is ultimately why they cannot be considered as international stages.

Tectonic evolution

During the Carboniferous, northern England was located on the southern margin of the Laurussian plate (Fig. 2). In the late Devonian to early Carboniferous, there was a northward subduction of the oceanic plate attached to Gondwana below the Laurussian plate. This resulted in a regime of back-arc extension, causing the reactivation of earlier basement lineaments in northern England to produce a series of tectonic blocks and basins. By late Mississippian times, consumption of the oceanic plate resulted in collision of the Gondwana and Laurussia plates. Crustal thickening and foreland basin development was evident, particularly in southern Britain, by the end of the Visean. However, in northern England the influences of the deformation are not evident until the end of the Carboniferous.

The main tectonic influence on northern England during the Mississippian was the north–south extension and thinning of the lithosphere. This was not a simple effect, because of the complexity of pre-existing basement lineaments that reactivated during this phase of extension. Structural highs, such as the Alston and Askrigg blocks of northern England (Fig. 3, *opposite*) are associated with slow subsidence rates, development of shallow seas and the formation of platform carbonates. The main subsidence was taken up in grabens and half-grabens, such as the Craven Basin, Gainsborough Trough and Widmerpool Gulf, which tend to be associated with deeper basinal successions typified by sedimentation from suspension or turbidity currents.

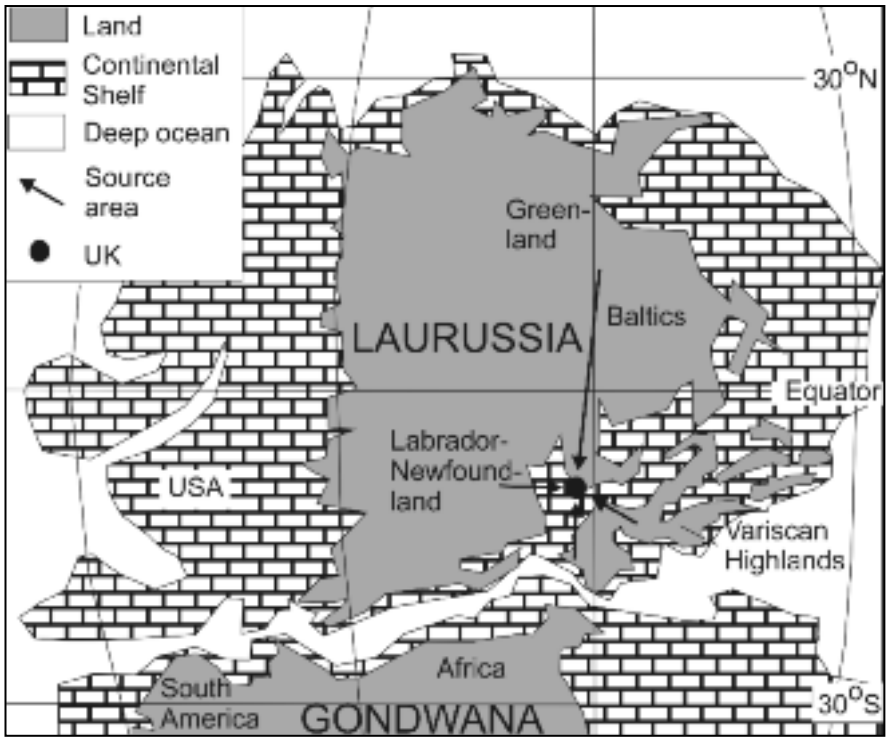


Figure 2 (above) Plate tectonic reconstruction for Mississippian times (c. 340Ma). Northern Britain was located just south of the Equator, with northward migration of the Laurussian Plate resulting in a location just north of the Equator by the end of the Carboniferous. The arrows illustrate the provenance or source areas of the deltaic systems evident during Namurian and Westphalian times. There are four main source areas: (1) the old Caledonian Mountain belt located between Greenland and Scandinavia, with major rivers flowing southward across Britain from this highland area; (2) a source from the west, between Newfoundland and the eastern seaboard of Canada, which because there was no Atlantic Ocean at that time, was close to the west of Ireland. (3) and (4) the other two sources are linked in that they are part of the newly formed Variscan highlands, with a source from the south-east (central Europe) and a source from the south (France and Iberia), respectively. Also, note that northern England was located at the end of a long arm of sea, which extends several thousand kilometres. The nearest open ocean is out towards the southern USA. (Palaeogeographical reconstruction adapted from model produced by Ron Blakey, NAU Geology: www.jan.ucc.nau.edu/~rcb7/index.html).

This linked series of small sub-basins eventually evolved during the Pennsylvanian into the larger Pennine Basin. The Southern Uplands and the Wales–Brabant High formed persistent upland areas during the Carboniferous, defining the northern and southern boundaries of the Pennine Basin, respectively.

Climate and sea level influences on sedimentation

A significant factor in the evolution of sedimentary successions during the Carboniferous is climatic change. This, in part, reflects a northward movement of Britain across the Equator, and the global change from greenhouse to icehouse conditions, with resultant instigation of dramatic sea level fluctuations.

During the early Tournaisian there was a broad marine transgression (Fig. 4, *opposite*), probably reflecting subsidence associated with the phase of back-arc extension rather than a sea level rise. The Tournaisian and the early Visean were characterised by relatively small and infrequent sea level fluctuations and a stable climate, typically semi-arid with short wetter intervals.

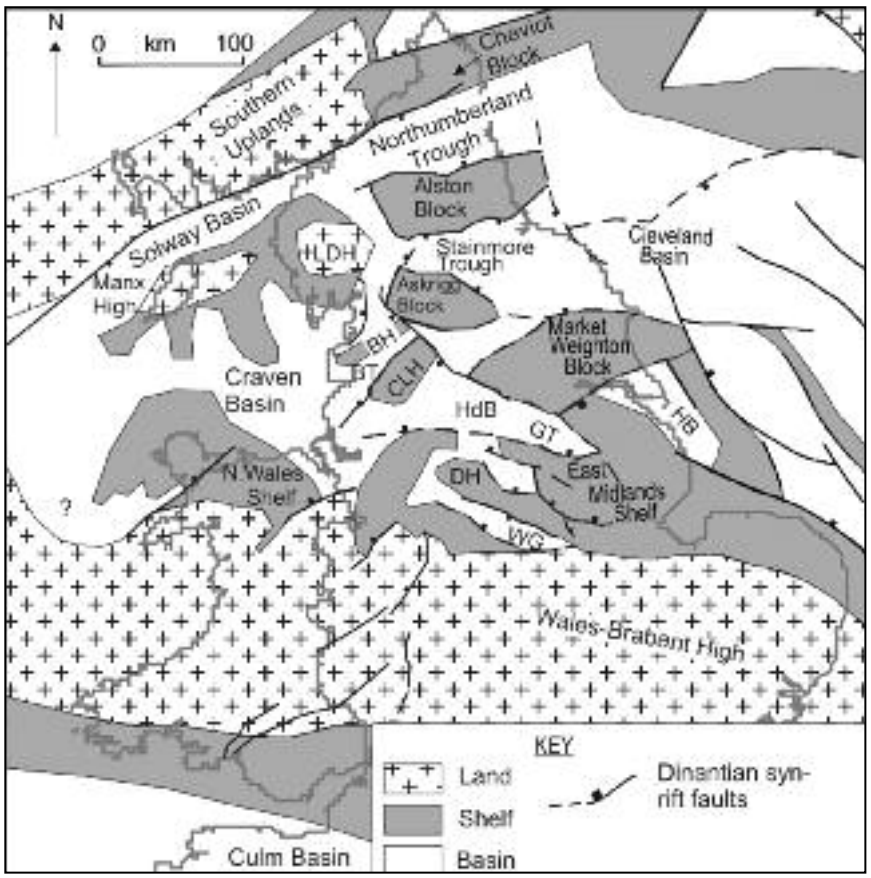
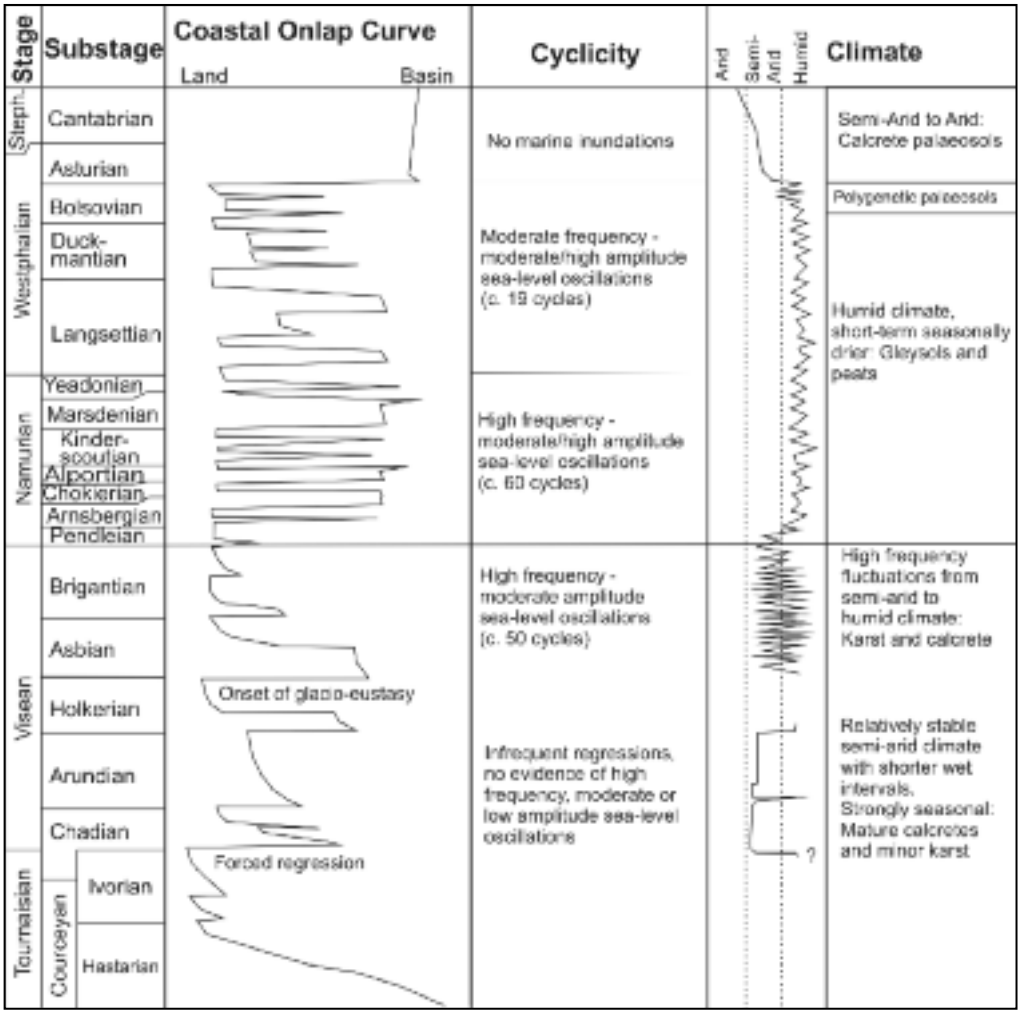


Figure 3 (right) Tectonic framework during the Mississippian showing the main structural highs, evident as upland areas or shallow shelf seas, and deeper water basinal areas. BH – Bowland High; BT – Bowland Trough; CLH – Central Lancashire High; DH – Derbyshire High; GT – Gainsborough Trough; HB – Humber Basin; HdB – Huddersfield Basin; LDH – Lake District High; WG – Widmerpool Gulf (redrawn from Waters and Davies 2006).

Figure 4 (below) Carboniferous sea level and climatic record. The coastal onlap curve provides an impression of relative sea level rise, with highest levels towards the left. The climate curve attempts to show variations of apparent aridity to humidity, based upon sedimentological features (from Waters and Davies 2006).



By Asbian and Brigantian times, there was a change to sea level fluctuations with both a higher frequency (Fig. 4), about 50 cycles, and higher amplitude, between 10–50m. At the same time there were higher-frequency fluctuations between semi-arid and humid climatic conditions. This suggests that glacio-eustatic controls of both sea level and climate started to dominate at this time. Intense glaciations may have brought about short-term seasonally drier climates, whereas ice melting resulted in sea level rises and a potentially wetter equatorial climate. However, research suggests that at this time there are no major ice sheets forming across Gondwana, with glaciation restricted to sub-alpine upland environments (Fielding *et al.* 2008).

The main phase of glacial eustacy occurred during Namurian times, with high frequency sea level variations, up to 60 cycles, and amplitudes of up to *c.* 60m. High-amplitude sea level changes persisted into the Westphalian, though with a lower frequency; 19 or 20 Coal Measures cycles are associated with marine flooding events. There was, however, consistency in a humid climate during the Namurian and Westphalian as a result of the equatorial location. However, toward the end of the Westphalian and into the Stephanian, there is no evidence of any further marine invasion in Britain and there was a change towards a semi-arid to arid climate. This may, in part, be due to the northward migration of Laurussia at the time, but also could be related to a rain-shadow effect, as Britain was located north of the growing Variscan mountain belt.

Lithostratigraphy

The BGS has over recent years been involved in the simplification of Carboniferous lithostratigraphy, with the results published by Waters *et al.* (2007; 2009), which can be freely downloaded from the BGS website (http://www.bgs.ac.uk/downloads/browse.cfm?sec=1&cat=2). The scheme was designed to rationalise the plethora of formation names found in the Carboniferous of northern Britain. It also aimed to develop a group nomenclature more representative of the sedimentological evolution during the Carboniferous by subdividing the succession into broad sedimentary facies associations (Fig. 5, *opposite*):

1. The Continental and peri-tidal facies is well developed in the Stainmore Trough between the Askrigg and Alston blocks, represented by the Ravenstonedale Group and limited in age to the Tournaisian and early Visean;
2. the heterolithic clastic and non-marine carbonate facies, restricted within northern England to the Northumberland Trough–Solway Basin as part of the Border Group and of early Visean age;
3. the platform carbonate facies, with distinct group names for the different highs — in northern England the facies are largely represented by the Great Scar Limestone Group; other platforms are associated with deposition of the Bowland High and Peak Limestone groups — all largely Tournaisian to Visean in age;
4. the hemipelagic facies comprises mainly suspension deposit mudstones with some turbidite deposits, represented by the Craven Group — they accumulated in part at the same time as the platform carbonates, but within the deeper water basins, ranging from Visean to Namurian age;
5. the Yoredale,
6. the Millstone Grit and
7. the Coal Measures facies, comprising markedly cyclic successions — they were deposited at a time of marked glacial eustacy, major sea level changes inducing the cyclicity, but with each facies having different characteristics, permitting differentiation between the three groups;
8. the Barren Measures, representing a return to almost the same semi-arid environment conditions that existed at the beginning of the Carboniferous — Red-beds dominate, coal seams are minor or absent. This facies, of late Westphalian to Stephanian, of very limited extent in northern England, includes parts of the Ingleton Coalfield.

Tournaisian: early basin evolution

During the Tournaisian there was a regime of marine transgression, particularly well developed in southern Britain and southern Ireland, with formation of a widespread platform carbonate succession (Fig. 6a, *page 8*). These carbonates did not extend far into northern England, where areas of emergent land were extensive. Between these uplands, alluvial plains are shown extending across much of northern and central England; realistically, the alluvial deposits are based on a small number of exposures and deep boreholes, so the full extent of these plains is uncertain. The Ravenstonedale Group of the Stainmore Trough is representative of these alluvial plain deposits. Pebbly sandstones dominate, typically red owing to deposition within an oxidising environment and with dominant calcrete palaeosols, suggesting a semi-arid environment. This facies locally passes into marginal marine flats where there is development of ferroan dolostones and evaporates, such as gypsum and anhydrite, again indicating a semi-arid environment.

Visean: block and basin controls on sedimentation

By early Visean times prominent upland areas were developed along the Wales–Brabant High and Alston Block–Lake District High. The dominant lithofacies are platform carbonates. However, incipient development of the Craven Basin, with formation of deeper-water hemipelagic mudstones represents drowning of earlier Tournaisian platform carbonates (Fig. 6b).

In Yorkshire, the classic development of platform carbonates is associated with the Great Scar Limestone Group of the Askrigg Block. This is a tilt-block high that passes northwards to the half-graben of the Stainmore Trough (Fig.7, *page 9*). The continental and peri-tidal facies of the Ravonstonedale Group was prevalent in the deeper part of the basin. The marine carbonates gradually onlapped the tilt-block high so that by Arundian and Holkerian times the marine carbonates extended across the tilt-block high. From late Holkerian to early Brigantian times the southern flank of the shelf, close to the Mid Craven fault system was marked by Cracoean buildups of knoll reefs and shelf-edge tracts. This formed an abrupt margin between the platform carbonates and the deep-water hemipelagic shales, which form the Craven Group.

There is broadly a transition across all of the UK Carboniferous platform carbonate successions from thinner, darker grey Arundian-Holkerian limestones to thicker-bedded pale grey Asbian-Brigantian cyclic limestones, and it is the latter that form the classic limestone pavements of the Yorkshire Dales. During the early Visean the platform carbonates are interpreted as being deposited in a gently sloping carbonate ramp with varying water depths. A significant feature was the formation of mud-mounds,

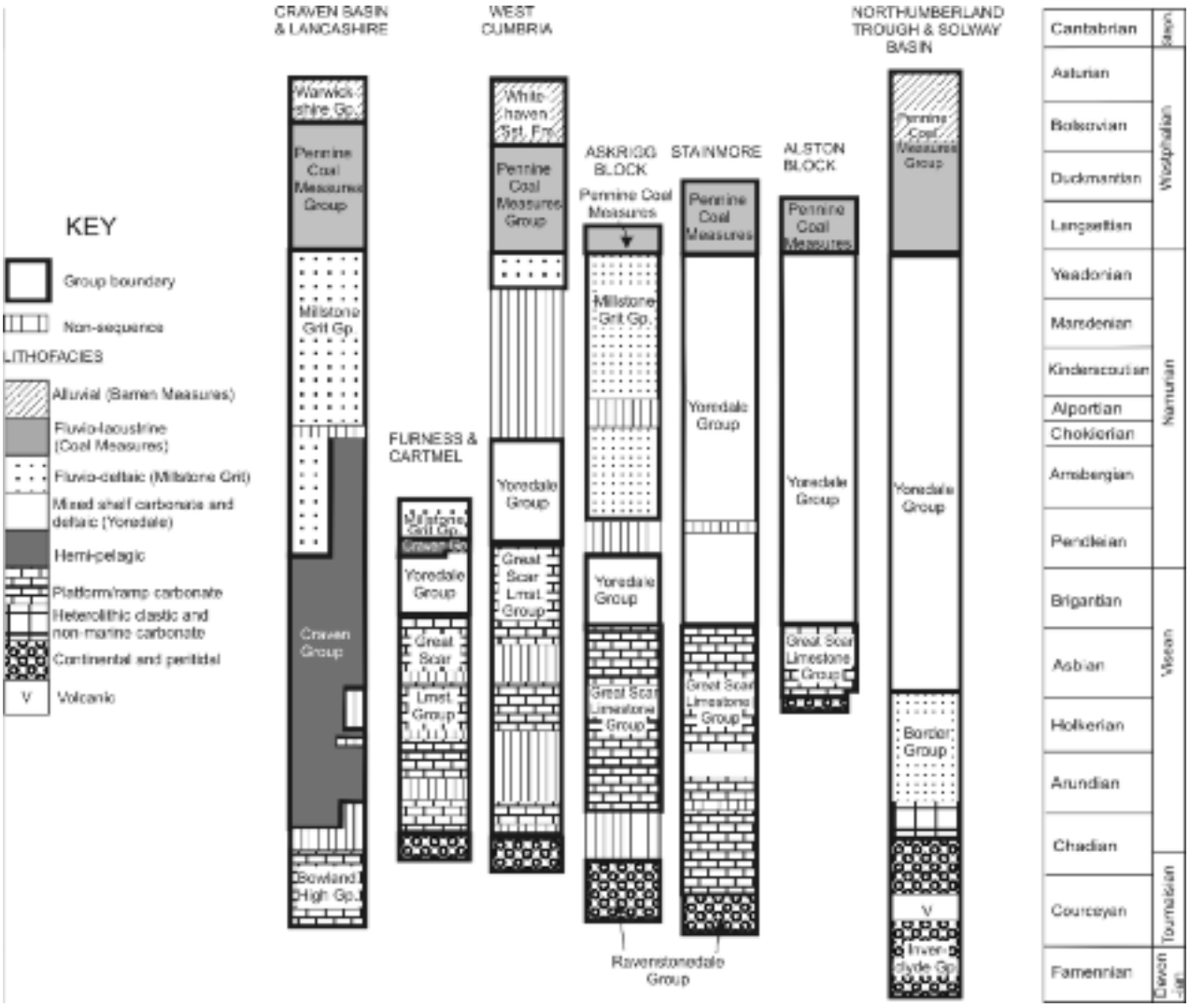


Figure 5 Carboniferous lithostratigraphy of northern England (from Waters and Davies 2006 and Waters et al. *2007).*

also known as knoll reefs and Waulsortian reefs, mainly formed from microbial framework lime muds. The mud-mounds were formed in water depths up to *c.* 280m, with different communities prevalent depending on the location of the mounds. One of the characteristics is the presence of algae, not of corals, as the main framework builders. The mud-mounds tended not to be present at very shallow depths, where a high siliciclastic influx and mobile carbonate shoals occur.

During the late Visean the reefs built upwards and outwards to form apron (or Cracoean) reefs separating a distinct shallow shelf from reef slope deposits. The apron reefs limited resedimentation of deposits through storm or wave activity, promoting an increase in relative height, and increasing the slope angle and marking the break between shelf and basin deposition. The transition between the two platform types broadly coincides with the possible Asbian–Brigantian glacio-eustatic event, suggesting that rapid sea level fluctuations may drive the formation of apron reef flanked shelves. A distinctive feature of these late Visean carbonates is the presence of up to eight pot-holed bedding surfaces, overlain by thin mudstones. These palaeokarstic surfaces are inferred to indicate periodic emergence, possibly in response to glacio-eustatically driven sea level falls. The marginal Cracoean reef limestones are well developed along the southern flank of the Askrigg Block. They can have a knoll-like geometry or as laterally broader shelf-edge apron reef. Up to 100m of succession are dominated by massive wackestones with abundant crinoids and productid brachiopods; corals, although common, did not have the framework-building characteristics of modern reefs, that role being largely occupied by algae.

By Brigantian (late Visean) times, the platform carbonates were most extensively developed on the flanks of the Wales–Brabant High, such as the Peak District (Fig. 6c). The Askrigg and Alston blocks were covered extensively by the Yoredale lithofacies, characterised by upward-coarsening cycles. The basal, comparatively thin marine carbonates, represent the maximum flooding surfaces. They are laterally extensive and are used to help correlate successions regionally. Marine shales pass up into commonly thin tabular quartzitic sandstones, mainly fine- to medium-grained. The sandstones typically represent shallow lobate deltas affected by marine reworking following abandonment. Locally, fluvial channel sandstones are present. Cycles are commonly capped by seatearth palaeosols and thin coals. Tucker *et al.* (2009) have presented evidence for the main cycles to represent short orbital eccentricity cycles of *c.* 112kyr. Studying the Great Limestone, they recognised limestone-mudstone couplets representing millennial-scale environmental changes, suggesting that the muds represented high-frequency sea level rises.

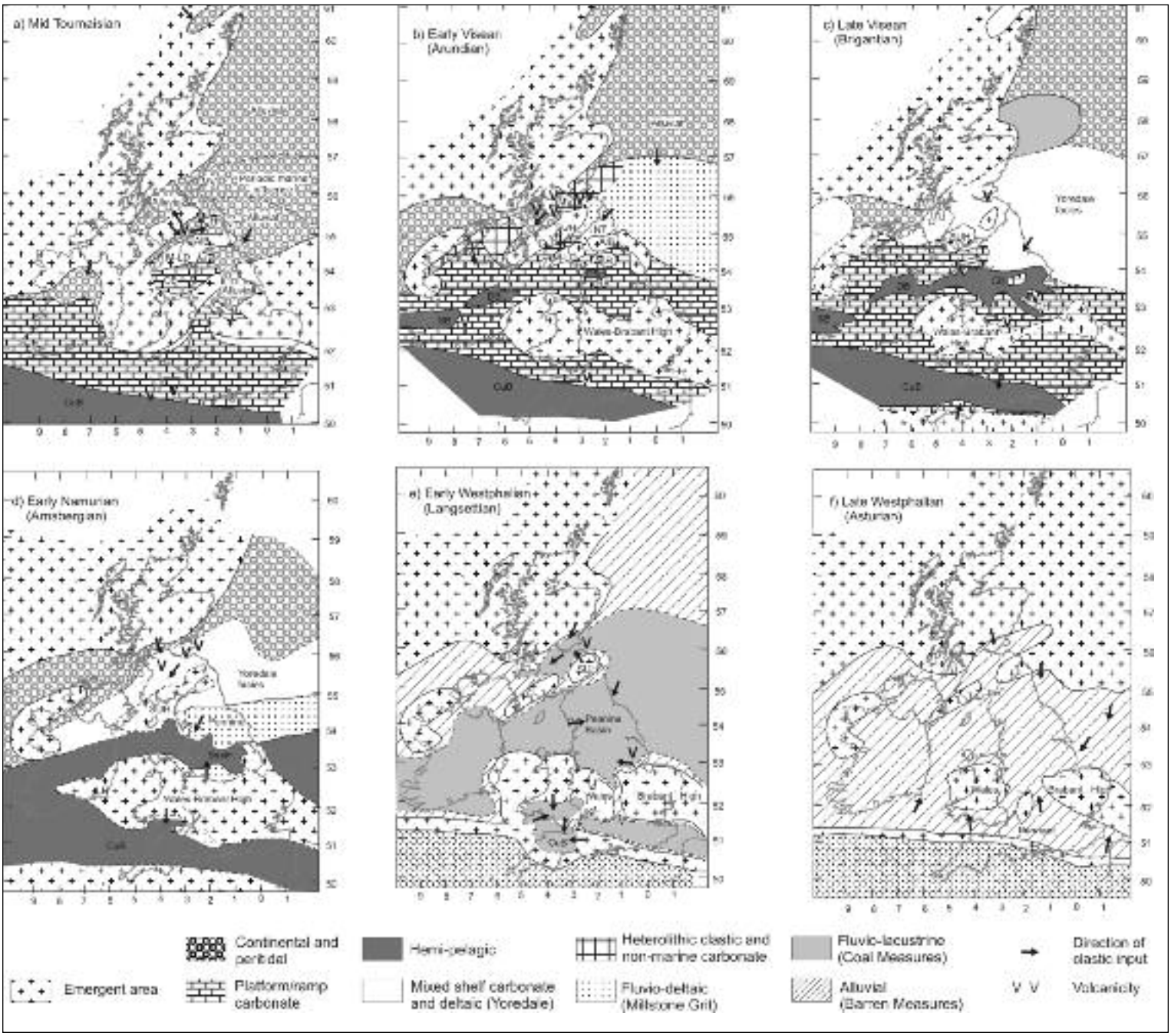


Figure 6 Palaeogeographical reconstructions showing the distribution of the main facies associations shown in Figure 5. (a) Mid Tournaisian, (b) Arundian (early Visean), (c) Brigantian (late Visean), (d) Arnsbergian (early Namurian), (e) Langsettian (early Westphalian) and (f) Asturian (late Westphalian) (from Waters and Davies 2006 and Waters et al. *2007).*

To the south, within the Craven Basin, the hemipelagic lithofacies of the Craven Group were being deposited at the same time as the Yoredale Group on the Askrigg Block. The Craven Group is represented by dark carbonaceous mudstones, formed by the slow accumulation of suspended terrigenous fine sediments below storm wave bases and probably at water depths in the order of >100m. The late Visean succession was deposited marginal to a carbonate platform and hence includes carbonate turbidites, with sharp bases and gradational tops. Carbonate breccias and slump structures are common within slope deposits. Namurian parts of the succession would more typically contain siliciclastic turbidites developed in the prodelta setting, signalling the advance of the main deltaic systems.

Namurian: deltaic deposition

By the early Namurian there was an extensive, linked basin, part-filled by hemipelagic shales of the Craven Group, bounded to the north by fluvio-deltaic sandstones of the Millstone Grit Group (Fig. 6d). Those sandstones present on the southern flank of the Pennine Basin are quartzitic and sourced from the Wales–Brabant High. Sandstones on the northern flank are quartz-feldspathic and are sourced far from the north.

The Millstone Grit and Yoredale groups differ in respect of their relative ‘marineness’: the Yoredale Group was associated with comparatively small-scale sea level rises, the maximum flooding surface being represented by limestone with shallow-water benthic communities; by contrast, in the Millstone Grit Group the main flooding events were associated with marine

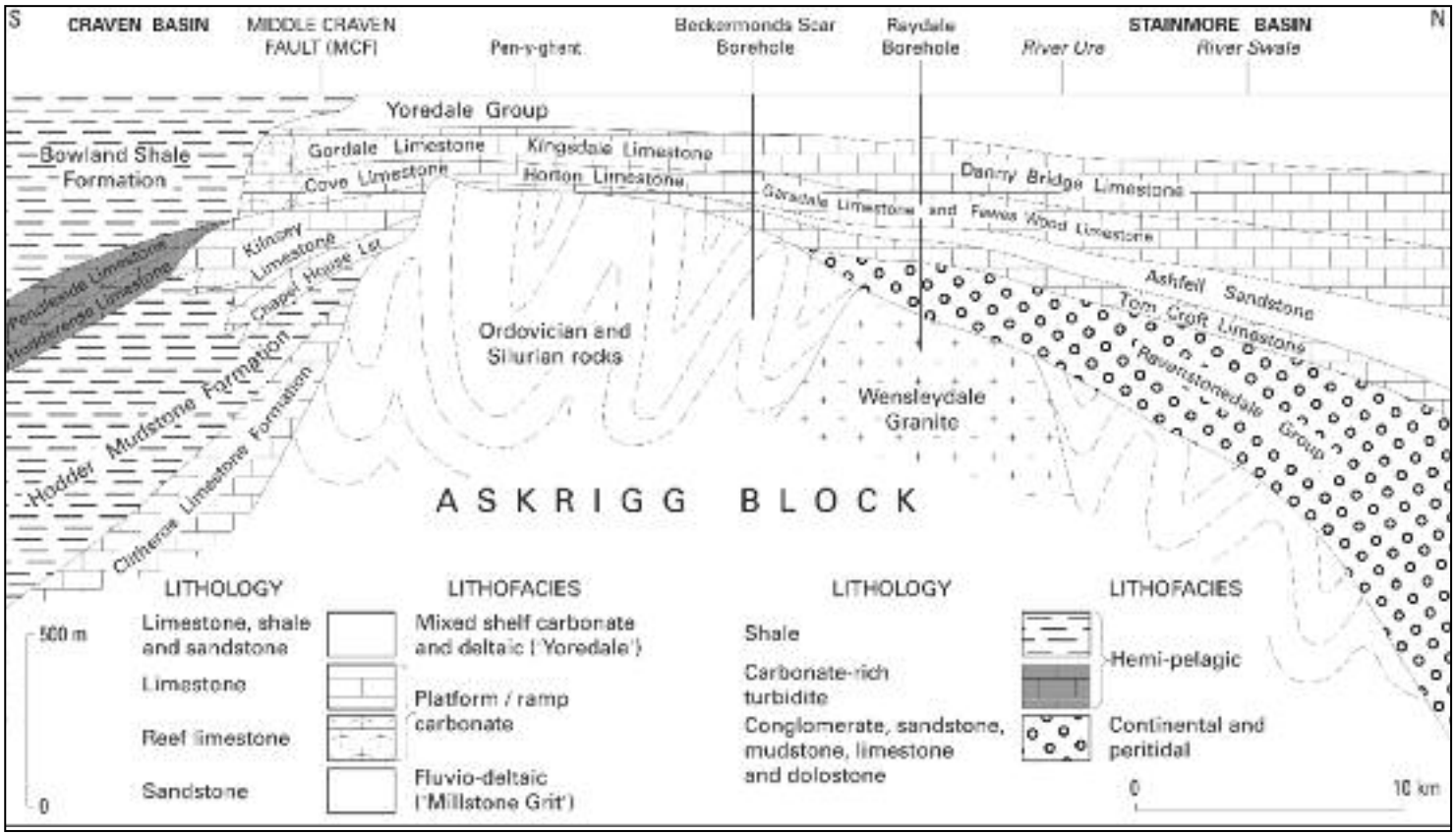


Figure 7 A schematic N–S section showing the correlation of Tournaisian and Visean across the Craven Basin–Askrigg Block–Stainmore Trough (from Waters and Davies 2006).

bands commonly containing ammonoids (goniatites); these fully marine pelagic feeders accumulated on an anoxic basin floor free of benthic fauna and, because of the high sea level stand, minimal sediment input. Because the ammonoids evolved so rapidly, the majority of marine bands are associated with a new diagnostic species. During the Namurian, of 13myr duration, there are some 60 marine bands, so, on average, the cycles are *c.* 200,000 years each in duration.

In the south, delta slope and turbidite fans of the Morridge Formation represent strata of Millstone Grit lithofacies with proto-quartzitic sandstones sourced from the south (Fig. 8, *overleaf)*. The main development of quartz-feldspathic fluvio-deltaic sandstones prograded gradually southwards into the Central Pennine Basin. Consequently, in the central part of the basin, the Bowland Shale Formation (Craven Group) extended up into the Kinderscoutian. The first phase of basin infill was associated with deposition of deep-water turbidite-fronted deltas. During the Pendleian and Arnsbergian the focus of deposition was in the northern flank of the basin. By late Arnsbergian times this part of the basin had been largely infilled and sedimentation rates broadly matched subsidence rates, such that much thinner cycles of shallow-water sheet-like deltas dominated and turbidite deposits were absent. During the Kinderscoutian there was a prominent increase in fluvial discharge that resulted in the southward progradation of the focus of deposition of turbidite-fronted deltas (including the Mam Tor Sandstones), which again rapidly infilled that part of the basin. The process repeated itself with the migration of turbidite-fronted deltas to the southern margin of the basin during Marsdenian times. By the end of the Marsdenian, the early Carboniferous block and basin topography had been entirely buried beneath fluvio-deltaic sediments and basinal topography was subdued.

Three examples of typical Millstone Grit Group depositional features are illustrated:

1. At the time of deposition of the Kinderscout Grits in Yorkshire, farther to the south in Derbyshire, there was deposition of a thick succession (up to 135m) of thin interbeds of siltstone and sandstone, known as the Mam Tor Sandstone. This is interpreted as a distal turbidite apron, developed on a delta slope, basin-ward of the Kinderscout Grit fluvial system. The beds are overlain by thick-bedded coarse-grained lenticular sandstones of the Shale Grit, representing proximal turbidite lobes. The overlying Grindslow Shales comprise thin-bedded siltstones interpreted as delta slope deposits, with coarse- to very coarse-grained internally massive sandstones representing turbidite feeder channels.
2. Current work on revision of the Derby Sheet is concentrating on looking at another turbidite-fronted delta system, the Ashover Grit, of Marsdenian age. The turbiditic sandstones developed in advance of, and were subsequently overridden by, the fluvial Ashover Grit and show large-scale, syn-sedimentary slumping. The large rotational blocks developed on the delta front were displaced towards the north-north-west on listric failures. There is also an earlier phase of syn-sedimentary deformation comprising low-angle shear planes associated with both extensional and compressional deformation, interpreted as slide sheets.
3. Above the Ashover Grit, one cycle contains a thick sandstone succession variously known as the Huddersfield White Rock in Yorkshire, Chatsworth Grit in the East Midlands and Brooksbottoms Grit in Lancashire (Fig. 9, *page 13*). There was an assumption that these sandstones were laterally equivalent. By analysing both maximum grain size and palaeocurrent directions throughout the Central Pennine Bain it was possible to recognise four distinct

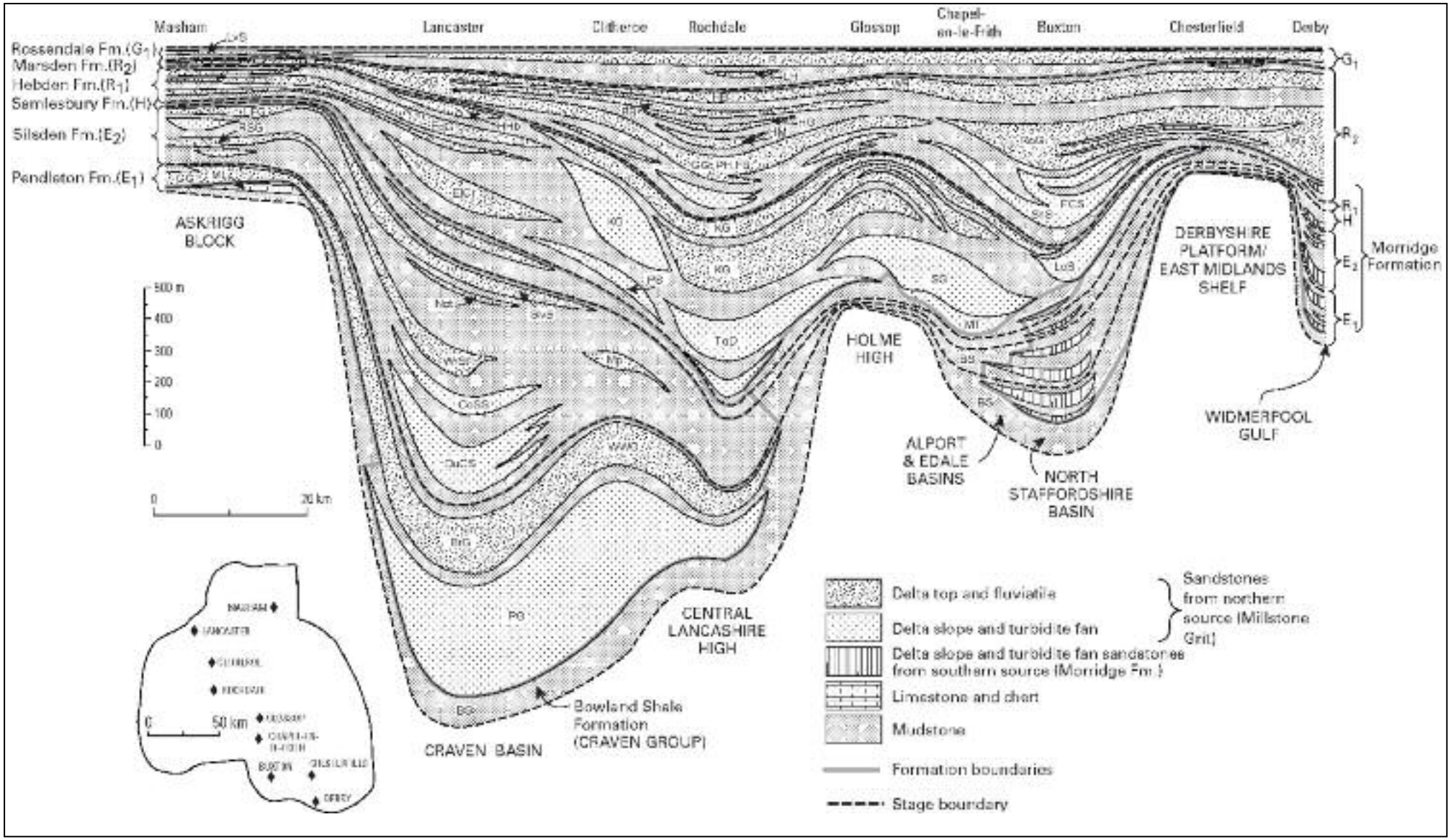


Figure 8 Distribution and lithofacies of the main sandstones of the Millstone Grit Group of the Central Pennine Basin. AsG – Ashover Grit; BB – Brooksbottom Grit; BrG – Brennand Grit; BS – Bowland Shale Formation; CG – Chatsworth Grit; CoSS – Cocklett Scar Sandstones; DuCS – Dure Clough Sandstones;EdG – Eldroth Grit; ElCr – Ellel Crag Sandstone; FB – Fletcher Bank Grit; FCS – Five Clouds Sandstones; GG – Grassington Grit; GGt – Gorpley Grit; GtG – Greta Grits; HB – Holcombe Brook Grit; HG – Hazel Greave Grit; HHb – Heysham Harbour Sandstone; HM – Helmshore Grit; HR – Huddersfield White Rock; KG – Kinderscout Grit; LFG – Lower Follifoot Grit; LH – Lower Haslingden Flags; LoS – Longnor Sandstones; LvS – Laverton Sandstone; ML – Main Limestone; Mp – Marchup Grit; MT – Mam Tor Sandstones; Not – Nottage Crag Grit; PG – Pendle Grit; PS – Parsonage Sandstone; PH – Pule Hill Grit; R – Rough Rock; RoG – Roaches Grit; RSG – Red Scar Grit; SG – Shale Grit; SlvS – Silver Hills Sandstone; SnS – Sheen Sandstones; ToD – Todmorden Grit; WrSt – Ward's Stone Sandstone; WWG-Warley Wise Grit. The dashed lines represent the time-lines of sub-stage boundaries; the thick lines are the boundaries between the new formations defined within the Millstone Grit Group (from Waters and Davies 2006 and Waters et al. *2009).*

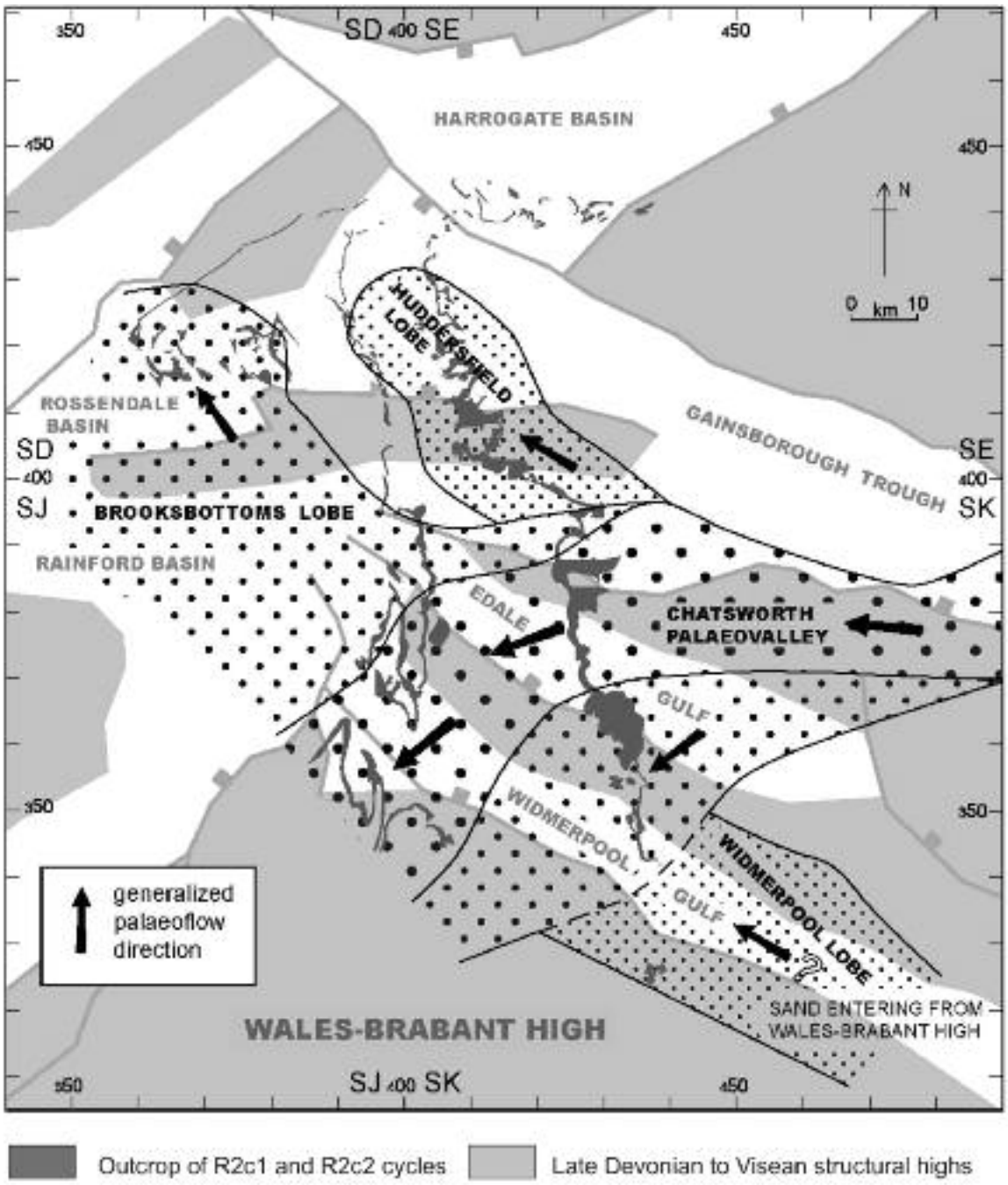


Figure 9 Distribution of the main sand bodies of the Huddersfield White Rock/Chatsworth Grit/ Brooksbottoms Grit (from Waters et al. *2008).*

sand bodies (Waters *et al.* 2008). The Huddersfield lobe is characterised by sandstones typically fine- to medium-grained, with local development of delta-top channels of coarse-grained sandstone, with a fanning of palaeocurrent direction from north-west to south-west. The Huddersfield lobe entered the basin from the east, perhaps controlled by a depositional low associated with the Gainsborough Trough. The Widmerpool lobe, mainly known from subsurface data, is of similar grain size and may be coeval with the Huddersfield lobe, but is associated with sedimentation in a separate system building along the Widmerpool Gulf. No palaeocurrent data is available for this area, but it is assumed that it entered from the south-est along the Widmerpool Gulf. The Brooksbottoms lobe has variable grain size, but the average is coarse-grained to granular. A similar fanning of palaeocurrent direction from north-west to south-west is evident. Progressively falling sea level resulted in the basin-ward stepping of the depositional system, a regressive systems tract, forming the Brooksbottoms lobe. The falling base level culminated in a fluvial sand body occupying an incised valley (the Chatsworth palaeovalley) *c.* 25km across and *c.* 50m deep. The sand body is typified by quartz pebbles in excess of 5mm. Palaeocurrents are consistently towards the west. The abrupt northern margin of the Chatsworth Grit incised valley is evident at Chinley Churn, south of Glossop. The Chatsworth palaeovalley can be compared with the modern Brahmaputra River, both representing low-sinuousity fluvial systems. During seasonal floods the entire Brahmaputra braid-plain, *c.* 8km wide, becomes flooded and the lozenge-shaped bars actively migrate downriver. During low-flow regime the water retreats to distinct channels, with erosion of the bar form producing reactivation surfaces. Relict braid-plain deposits flank the active system, with the entire fluvial succession being *c.* 20km wide, similar in scale to the Chatsworth palaeovalley.

To summarise, the Namurian sand bodies show a systematic relationship to sea level change. Because of the lengthy and sinuous nature of connections between the open sea and the Central Pennine Basin, the Maximum Flooding Surfaces (marine bands) are likely to coincide with a maximum of the sea level curve (Waters *et al.* 2008). During the early phase of the falling stage, deltas built out into the basin, as evident during deposition of the Huddersfield White Rock. During the late falling stage, there was basin-ward migration of the centre of deltaic deposition, evident with the Brooksbottoms Grit and ultimately with marked incision formed a broad palaeovalley that during the earliest rising stage part filled with fluvial sediments: the Chatsworth Grit.

A similar explanation has been proposed for the geometry of the Kinderscout Grits. Typically, downstream of the channel, sediments were transported by submarine feeder channels, bypassing the upper part of the delta slope, to accumulate as a delta-front apron of coalescing turbidite lobes. The distal to proximal transition of these turbidite lobes is seen as the Mam Tor Sandstone and Shale Grit. Sands bypassed the delta slope within feeder channels, leaving the slope starved of sands, forming the Grindslow Shales. During the rising stage the incised valley filled with thin, upwards-coarsening cycles associated with deposition of fine-grained Brown Edge Flags and Redmires Flag, representing the Transgressive Systems Tract. These sandstones cannot be traced outside the incised valley, where a thick, leached palaeosol equates with much of this interval.

Westphalian: coal-forming mires

The Westphalian is associated with deposition of the Coal Measures facies, which extended across the Pennine Basin (Fig. 6e). The extensional tectonics of the early Carboniferous had been superseded by a phase of thermal subsidence, caused by the cooling of the asthenosphere beneath tectonically thinned lithosphere. Isopachytes for combined Pennine Lower and Middle Coal Measures formed a broad bulls eye pattern, with their thinnest development at basin margins and greatest thickness (*c.* 1.5km thick) in the basin depocentre around south Lancashire (Fig. 10). Anomalous thicknesses occur across parts of northern England. It appears that the granite-rooted highs of the Askrigg and Alston blocks were isostatically buoyant during the Carboniferous, with little subsidence occurring during the Westphalian. The current distribution of Coal Measures strata, at outcrop and in the subsurface, represents subsequent tectonic isolation of what was a laterally continuous succession.

There are three formations within the Pennine Coal Measures Group: the Pennine Lower, Middle and Upper Coal Measures, the bases defined by prominent marine bands — the Subcrenatum, Vanderbeckei and Cambriense bands, respectively. Broad lithological changes are recognised, the lower part of the Pennine Lower Coal Measures is dominated by a number of flooding events, hence several marine bands, whereas the coal seams are generally much thinner and of poor quality. The main coal resource is within the upper part of the Lower Coal

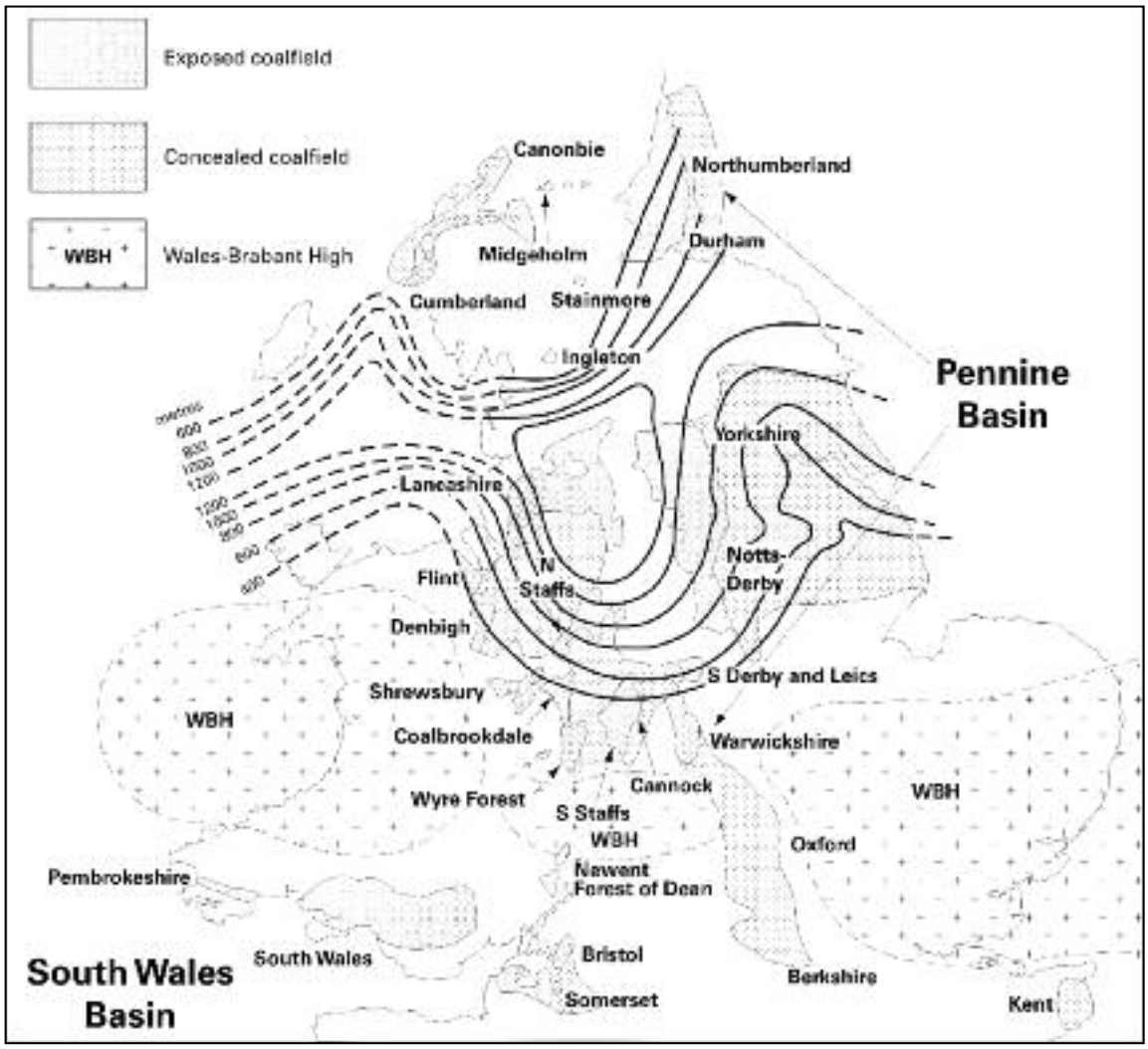


Figure 10 Distribution of Westphalian coalfields in England and Wales and generalised thickness of the combined Pennine Lower and Middle Coal Measures (from Waters and Davies 2006 and Waters et al. *2009).*

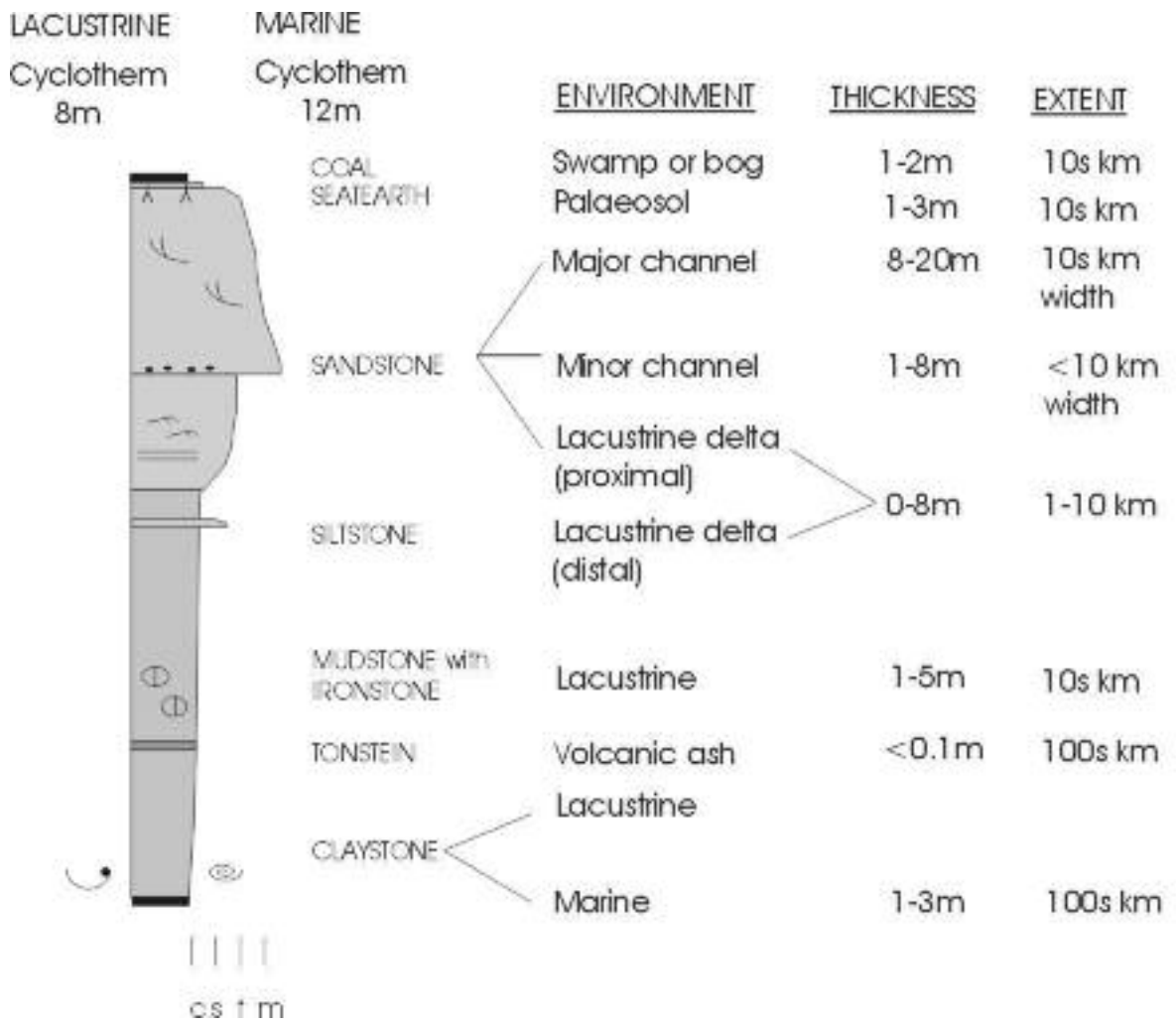


Figure 11 Typical Coal Measures cycle (adapted from Guion et al. *1995).*

Measures and the lower part of the Pennine Middle Coal Measures. Here, there are few marine flooding events and coals are thickly developed. In the upper part of the Pennine Middle Coal Measures, there is a reversion to an environment with a large number of marine bands, with the coals generally thinner and poorer quality. Within the Pennine Upper Coal Measures there are no more flooding events, the coals are generally thin, with significant distributary channels present in the upper part of the formation.

The Coal Measures lithofacies comprises cyclic successions of mudstone, siltstone, sandstone and coal, commonly known as cyclothems. A typical cycle is upwards coarsening, passing from lacustrine mudstone, through lacustrine deltas, locally capped by delta-top distributary channels of varying scale (Fig. 11). Ultimately, emergence is evidenced by the formation of a palaeosol and coal. Duff and Walton (1962) showed that in the East Pennine Coalfield, on average, there is a greater cyclothem thickness for cycles with the presence of a thin, basal, marine shale (12m), as opposed to a lacustrine shale (8m). It is possible that the accommodation space for many of the lacustrine cycles reflects a combination of regional thermal subsidence and compaction-related subsidence following distributary avulsion, producing the space for a new cycle to develop. In the case of marine cycles, a rise in sea level is likely to have enhanced the accommodation space formed by regional and compactional subsidence.

A typical Coal Measures swamp environment was associated with large tree-like clubmosses and tree ferns, growing on a floodplain with a permanently high water table, much like the modern day Amazon Basin. The trees and associated vegetable matter collected within anoxic conditions, in which the organic material did not oxidise and consequently accumulated to form the peat, which in turn was buried, compressed and heated to form coal.

In the East and West Midlands, many coal seams repeatedly split towards the north, away from the Wales–Brabant High, reflecting increasing subsidence rates towards the Pennine Basin depocentre. At the margins, where subsidence rates were low, peats had a long time to accumulate, forming few, but much thicker seams. The Staffordshire Thick Coal is up to 17m thick, which would equate with 170m thickness of peat formation. Some coals, particularly those below and above the marine flooding events, occur as single extensive coal seams.

Coal splits can also be seen on a much smaller scale in association with major distributary channels. East of Sheffield the Threequarters coal splits and increases in ash content towards the Silkstone Rock (Aitkenhead *et al.* 2002). On the north side this coal fails toward the channel and on the south has been removed by erosion by one of the multiply stacked channel sand bodies.

The majority of sand bodies within the Pennine Coal Measures Group are associated with minor lacustrine deltas or meandering channel systems (Fig. 11), with relatively sluggish flow velocities

and a low gradient profile. The delta-top floodplain within interdistributary areas may have been occupied by shallow freshwater lakes up to 10m deep, for at least part of the year. Breaches of levees marginal to the channels resulted in sheet-like, sharp-based crevasse splay deposits. The migrating channels generated laterally accreting point bar deposits. Abandoned meander loops formed ox-bow lakes, the abandoned channels commonly filling with peat rather than with channel sands, resulting in local development of swilley coals. In contrast to the topographical lows associated with ox-bow lakes, channel sand bodies compacted to a lesser degree and formed relative topographical highs, associated with thinner coal development.

Pioneering work using heavy minerals suites (mainly Monazite:Zircon, Chrome Spinel:Zircon and Garnet:Zircon ratios) combined with palaeocurrent data to distinguish sandstone provinces has provided the greatest resolution of the interplay of distinct fluvial systems within the Pennine Basin (e.g. Chisholm and Hallsworth 2005). They recognise four source regions (Fig. 2):

1. During the late Namurian and early Langsettian (the lower part of the Pennine Lower Coal Measures) the source region was from the north, but with sediments entering the basin from both the north and east. The sandstones are typically quartz-feldspathic and micaceous and locally can be medium- to coarse-grained and even pebbly. The source area is inferred to be from the margins of the Laurentia and Baltica plates in Norway or Greenland based upon the mixed ages of zircons and monazites of Archaean granulites, mid-Proterozoic sediments and Silurian granites.
2. During the deposition of the upper part of the Pennine Lower Coal Measures and lower part of the Pennine Middle Coal Measures the source region was from the west. Initially there is some recurrence of the northern influence with deposition of the Grenoside Sandstone. These western-sourced sandstones are typically finer- grained and more clay-rich and include chrome spinels, indicative of an ophiolitic source. The most likely candidate is Appalachia–Labrador–Newfoundland, which at the time was much closer to Britain than it is today.
3. During deposition of the upper part of the Pennine Middle Coal Measures and Pennine Upper Coal Measures the source region was from the Variscan orogen, located to the south-east. The sandstones are typically cleaner and quartz-feldspathic, and locally can be coarse-grained and pebbly. A source from central Europe is inferred, with river systems bypassing around the east of the Wales–Brabant High and entering the eastern part of the basin.
4. A final source represents an influence of a local southern source, possibly associated with the Wales–Brabant High. This influence is not observed farther to the north in the Yorkshire Coalfield.

By the Late Westphalian and Stephanian sedimentation was dominated by deposition of typically red-bed alluvial successions (Fig. 6f). These are particularly evident along the southern margin of the Pennine Basin, and have recently been described along the northern margins at Canonbie and West Cumbria. However, over the Yorkshire area they are mostly absent, removed by the end Carboniferous Variscan deformation. Uplift associated with this deformation event is largely concentrated in the basin depocentre, with up to 4km uplift estimated, with *c.* 1km to 2km of uplift in Yorkshire. Limited expression of these red-beds, forming what has become known as the Warwickshire Group, are evident in small outliers such as the Ingleton Coalfield.

Acknowledgements

This contribution is based upon the work of many colleagues, too many to mention, who have helped to develop and refine our understanding of the evolution of the Pennine Basin. Few references are quoted in this presentation, but the sources of much of the information can be determined by use of the key references quoted. The author publishes with the permission of the Executive Director, British Geological Survey, Natural Environment Research Council.

References

Aitkenhead, N., Barclay, W. J., Brandon, A., Chadwick, R. A., Chisholm, J. I., Cooper, A. H. and Johnson, E. W. 2002 *British Regional Geology: The Pennines and Adjacent Areas*. London: HMSO for the British Geological Survey

Chisholm, J. I. and Hallsworth, C. R. 2005 'Provenance of Upper Carboniferous sandstones in east Derbyshire: role of the Wales-Brabant High'. *Proc Yorkshire Geol Soc* **55**, 209–33

Duff, P. M. D. and Walton, E. K. 1962 'Statistical basis for cyclothems: a quantitative study of the sedimentary succession in the East Pennine Coalfield'. *Sedimentol* **1**, 235–55

Fielding, C. R., Frank, T. D., Birgenheier, L. P., Rygel, M. C., Jones, A. T. and Roberts, J. 2008 'Stratigraphic imprint of the Late Palaeozoic Ice Age in eastern Australia: a record of alternating glacial and nonglacial climate regime'. *J Geol Soc* **165**, 129–40

Guion, P. D., Fulton, I. M. and Jones, N. S. 1995 'Sedimentary facies of the coal-bearing Westphalian A and B north of the Wales-Brabant High', *in* Whateley, M. K. G. and Spears, D. A. (eds) *European Coal Geology*. London: Geol Soc Spec Publ, 45–78

Tucker, M. E., Gallagher, J. and Leng, M. J. 2009 'Are beds in shelf carbonates millennial-scale cycles? An example from the mid-Carboniferous of northern England'. *Sedimentary Geol* **214**, 19–34

Waters, C. N. and Davies, S. J. 2006 'Carboniferous extensional basins, advancing deltas and coal swamps', *in* Brenchley, P. J. and Rawson, P. F (eds) *The Geology of England and Wales* (2 edn). London: Geol Soc, 173–223

Waters, C. N. (ed and comp) 2008 'Stratigraphical chart of the United Kingdom: Southern Britain'. Nottingham, Keyworth: BGS

Waters, C. N., Browne, M. A. E., Dean, M. T., and Powell, J. H. 2007 *Lithostratigraphical Framework for Carboniferous Successions of Great Britain (Onshore)*. BGS Res Rep **RR/07/01**, 60

Waters, C. N., Chisholm, J. I., Benfield, A. C. and O'Beirne, A. M. 2008 'Regional evolution of a fluviodeltaic cyclic succession in the Marsdenian (Late Namurian Stage, Pennsylvanian) of the Central Pennine Basin, UK'. *Proc Yorkshire Geol Soc* **57**, 1–28

Waters, C. N., Waters, R. A., Barclay, W. J. and Davies, J. R. 2009 *Lithostratigraphical Framework for Carboniferous Successions of Southern Great Britain (Onshore)*. Nottingham, Keyworth: BGS Res **Rep RR/09/0**1

Dinosaur footprints on the Yorkshire coast

Dr Mike Romano (Geography Department, University of Sheffield

[Author's note: This paper is taken mainly verbatim from a recording of a lecture, and therefore has a different style of expression from that of a more formally written text. Please excuse any inconsistencies or errors that may have resulted from trying to revamp a transcript]

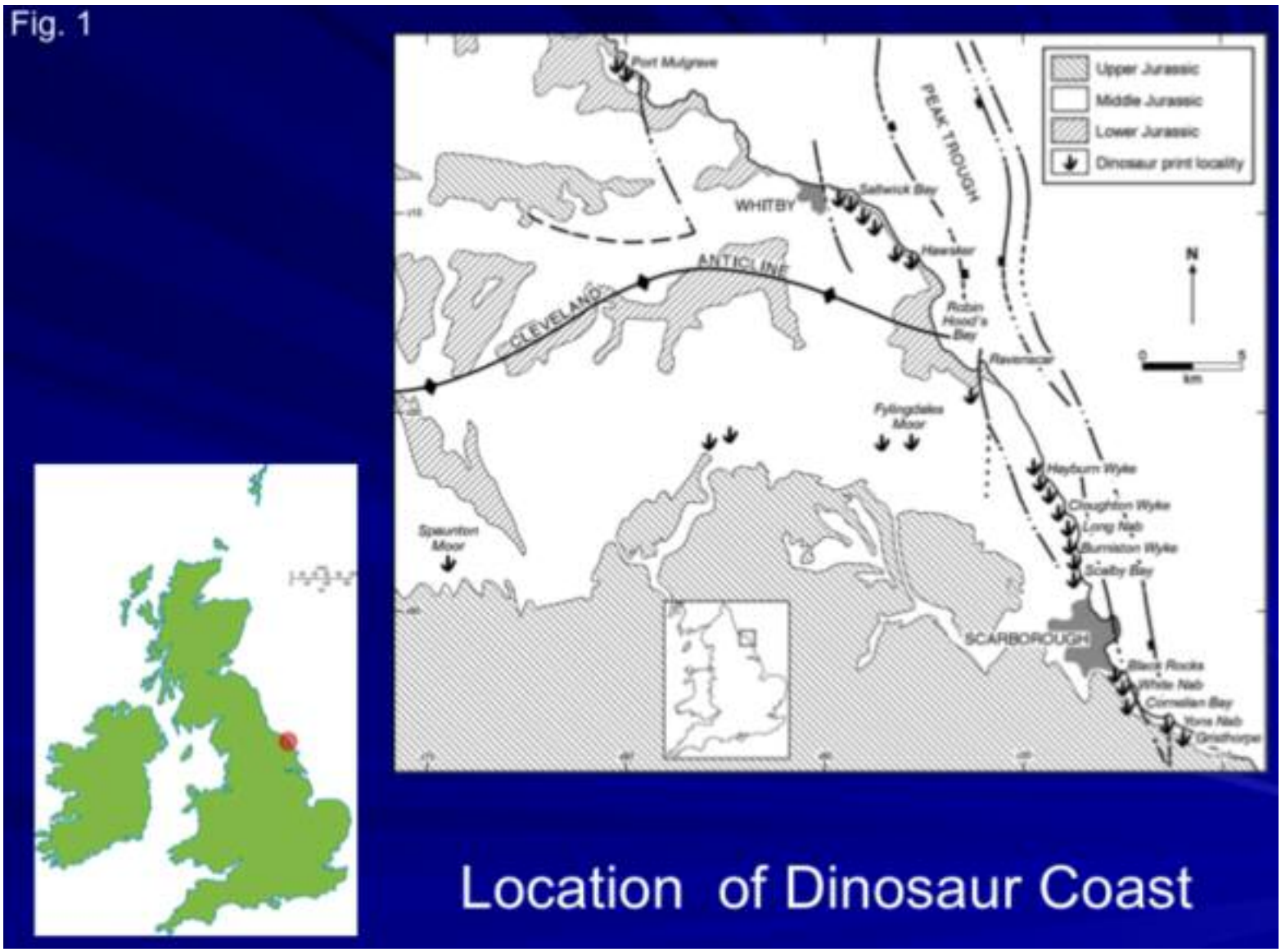
Much of the information that Dr Martin Whyte and I have on dinosaur footprints from the east coast of Yorkshire has been obtained from three major sources. The first is from volunteers of Earthwatch and Earthwatch International, who collectively spent many weeks over a 10-year period walking the east Yorkshire coast in all weathers searching for dinosaur footprints. In a short while we had amassed a database that we could hardly cope with, but still the records kept coming in. The second source stems from work by Martin Whyte and myself, together with our three postgraduate students and numerous undergraduate students from the University of Sheffield. The third source was, and still is, from the numerous enthusiastic amateur dinosaur hunters who continually roam the Yorkshire coastline and report back to us any interesting 'finds'.

The Yorkshire dinosaur coast

The Yorkshire coast is indeed a classic stretch of coastline. For many years researchers have pondered over the lithostratigraphy, the chronostratigraphy and the biostratigraphy, and really the dinosaurs footprints have only been a fairly recent phenomenon. The first paper published on the footprints was by Brodrick (a Lancastrian not a Yorkshireman), who in 1907 published a paper entitled 'A Find!!'. Actually so-called crocodilian footprints had been reported in 1895, but these were probably dinosaurian in origin. The slab of rock from which Brodrick described his footprints is presently embedded in a wall of Whitby Museum for all to see.

The stretch of coastline that yields the footprints is between Port Mulgrave in the north to just south of Scarborough (Fig. 1). When we first drew this map and put on dinosaur footprints where we had found them in the field, there were one or two sites inland and just a few more localities on the coast. Now we could just about cover that coastline with symbols of dinosaur footprints. They are everywhere, if you know where to look and if you know how to look. Even the Earthwatch volunteers

Fig. 1



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successfully started to find them after a day or so. In reality the prints are so common that they provided the name 'The Dinosaur Coast' (not to be confused with 'The Jurassic Coast' on the south coast of England). Although it may be argued that the Yorkshire epithet is a misnomer, since it is the traces that are common and not the actual dinosaur remains, there are now about 10 localities known from which dinosaur bones have been recovered; and the majority of these have been found since we started working on the sections.

The dinosaur prints occur in rocks of Middle Jurassic age in Yorkshire, since it is these rocks that are non-marine (or terrestrial). The Middle Jurassic rocks of Yorkshire accumulated in what is now known as the Cleveland Basin. During deposition of these non-marine sediments the area was a relatively flat coastal plain (Fig. 2). If, during the Middle Jurassic, you were standing at present-day Scarborough or Whitby, you would see a landmass (the Pennines) to the west and highlands (Scotland) to the north. Both of these upland areas supplied sediment to the Cleveland Basin by way of meandering rivers. The views of the ancient river meander belt from the cliff tops at Burniston and Scalby are justly famous. The nearest sea at the time was off the East Anglian coast or south coast of England. Occasionally the sea inundated the Cleveland Basin and gave rise to marine deposits. These latter rocks have yielded ammonites and other fossils that enable us to date the Middle Jurassic sequence as Aalenian–Bathonian.

The coastline is extremely unstable. Cliff erosion is proceeding at a fast rate; and although this may mean known dinosaur tracks are continually being covered up, it also results in landslides and rock falls that expose new tracks. So, although we do not have large bedding plane surfaces exhibiting trackways more than 100m long, as in some of the classic global sites, we make up for it by having vertical cliffs that expose the tracks in section, and a continual replenishment of the database.

Search for prints

As a consequence of the type of exposure we experience on the east coast, it is inevitable that initially we concentrated on preservation of the prints. It is important to understand how these prints are formed and it is convenient to recognise three types of preservation. The one that may be most familiar to you, when you take a walk on the beach or along a river or stream, is that which occurs when your foot is impressed in the sediment. When you take your foot out, the remaining mould can be filled sediment. In the example here the mould is made in mud, and it is filled in with sand (Fig. 3, *opposite*). When the mud and sand harden and the rock splits along the junction (the tracking surface), a 'surface print' results. A second type of preservation is known as an 'underprint'. In this scenario, the sequence of events is the same as for a surface print, but the rock may split along a number of different levels (Fig. 4, *opposite*). In this type of preservation,

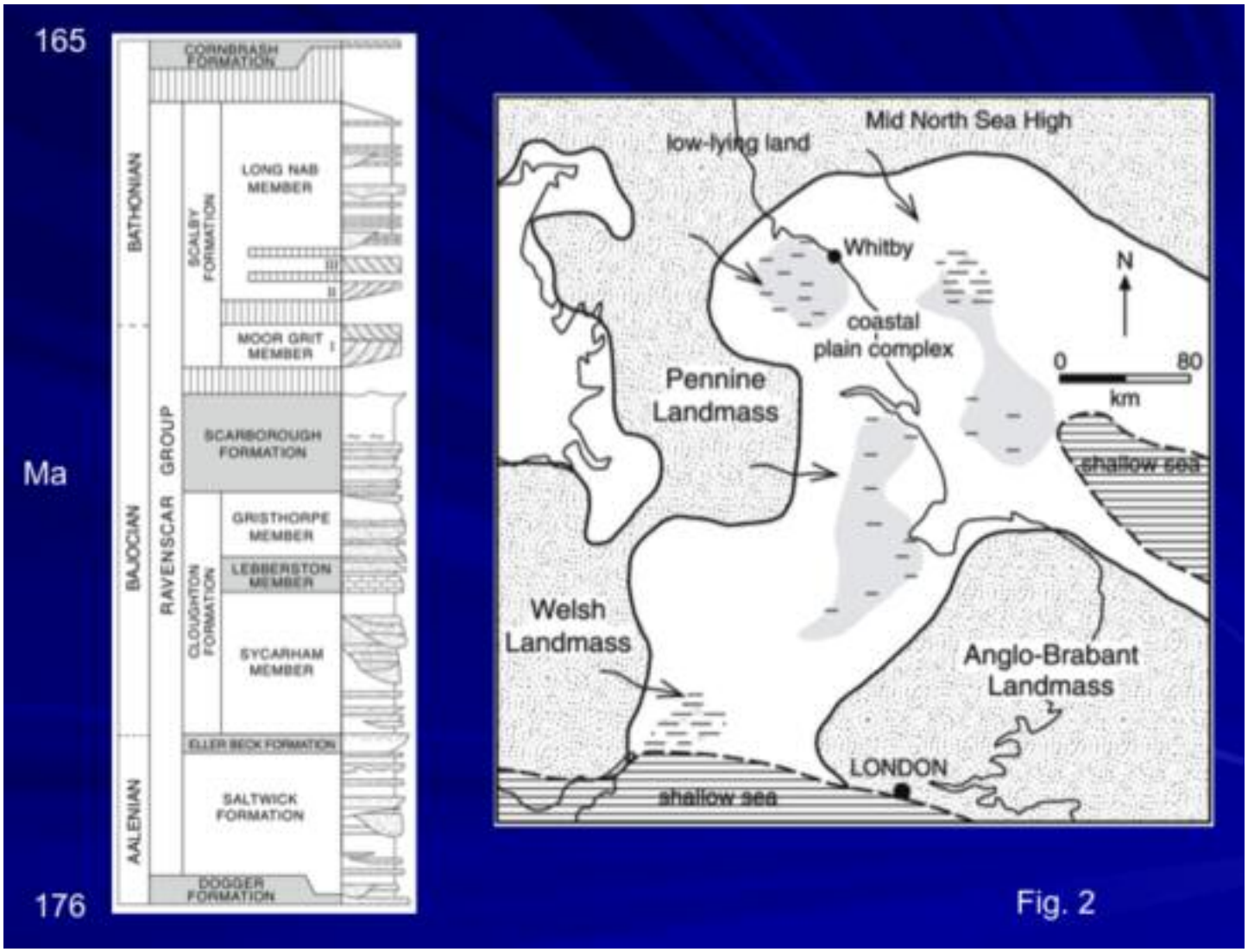
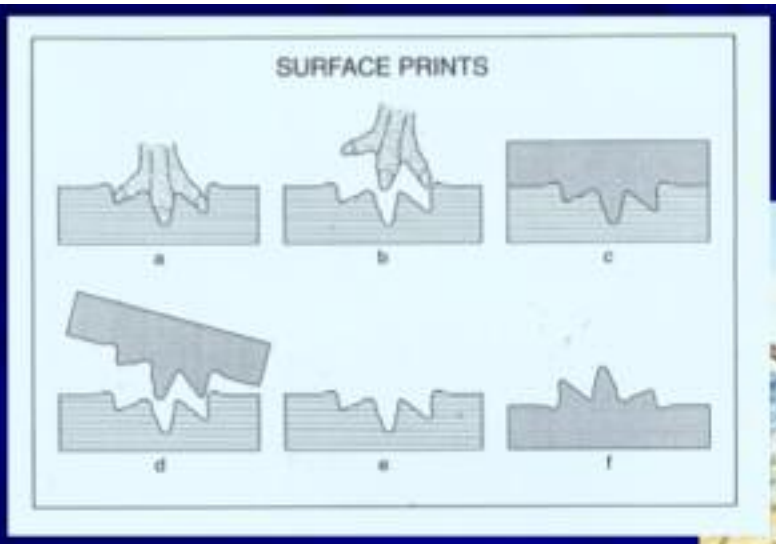


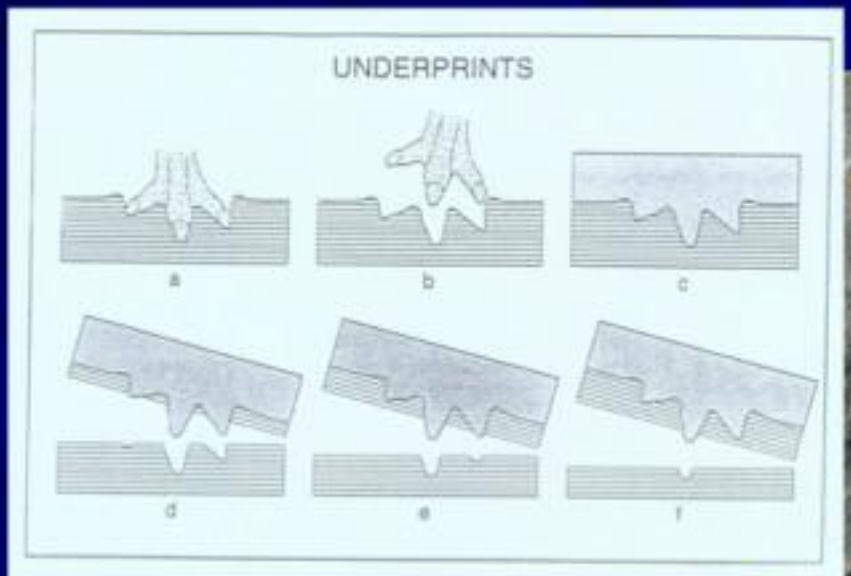
Fig. 2

Fig. 3



Preservation

Fig. 4



Preservation

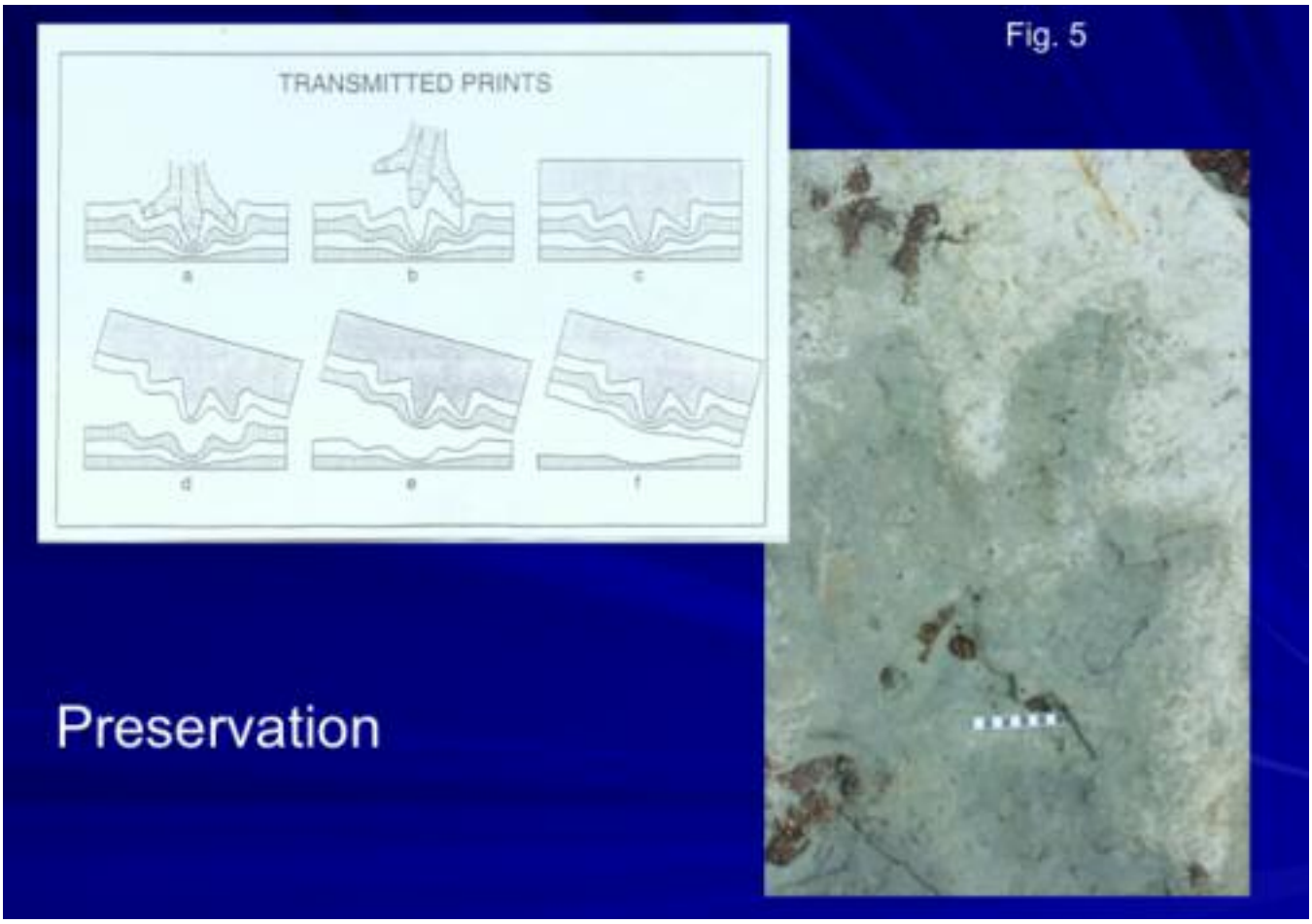
a print may exhibit only an imprint of a single digit (toe). Consequently such prints must be interpreted with care! A third type of print, and probably the most common, is known as a 'transmitted print' (Fig. 5). Think of a thinly bedded or laminated sediment. When the foot implants in it, and if the conditions are right, then the sediment layers are deformed, rather than punctured. The rock can subsequently split at different levels along particular laminae, or it can split horizontally through different layers. Whichever happens, it can result in a very complicated-looking print. Some American authors refer to these prints as 'ghost prints'. Clearly with this type of preservation, you can never be sure of the true length or width of the foot that made the print.

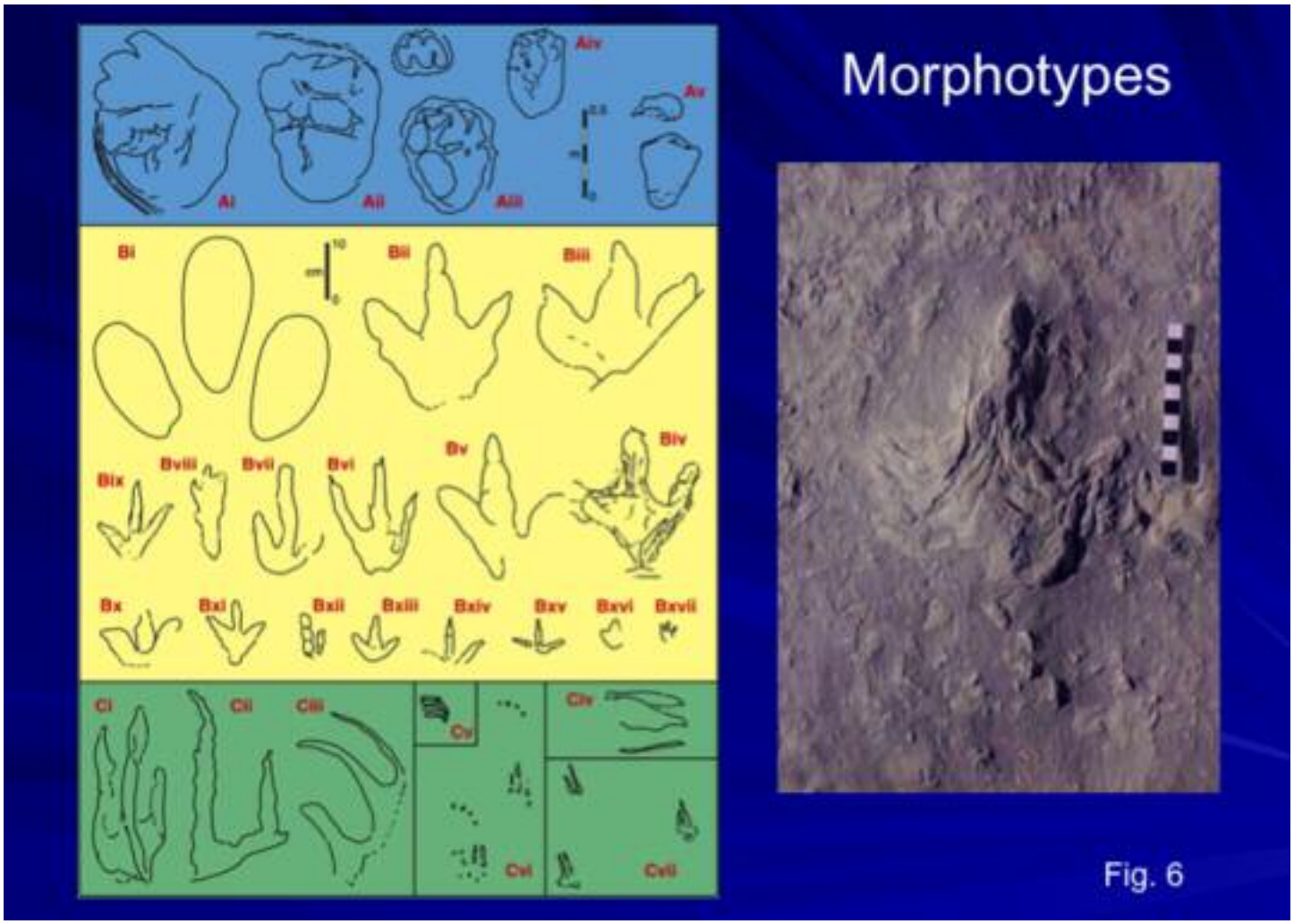
In 2003 we had arrived at a stage where we felt confident to present a paper that illustrated the range of prints that we had found. We referred to the different types as 'morphotypes', not as species. They certainly are not species, as they are not body fossils. For example, a human being (*Homo sapiens*) can make many different types of track depending what he or she is doing; i.e. based on behaviour, and only to a certain extent on the morphology of the foot (or hand) making the track. But we had an option to name them ichnogenera or even ichnospecies ('genera' or 'species' of trace fossils). However, at that stage of our studies we could only name one or two of them, and our knowledge of each was insufficient to designate a formal (ichno)taxonomic name. Altogether we identified 29 morphotypes (Fig. 6, *opposite*). If we had to put them into ichnospecies now, we would probably identify about 12 ichnospecies. But do those 12 ichnospecies represent 12 different animal types? Probably not — and that is another question.

Morphotypes and Groups

In illustrating the 29 morphotypes we arranged them into three groups. The prints in the top group (Group A) were made by habitual quadrupeds — animals that walked most of the time on four legs. These were probably made by sauropods. The middle group (Group B) are our tridactyl prints, made by animals that were habitual bipeds — they walked on two legs and they had three functional toes (although they may have had a small non-weight-supporting fourth digit at the back). The group at the bottom (Group C) is a bit of an oddball because that is our 'behavioural' group. It is a group where the prints are characterised by digit markings that are parallel to one another. We believe these prints represent a swimming behaviour, whereby the digits make parallel drag-marks in the sediment when making intermittent contact with the sediment surface.

In looking at these three groups in detail, we start with the tridactyl ones (Group B). These are by far the most common types of print and now that we are beginning to think about what animals made them we can recognise a group where the toes are quite divergent, no sharp claws and pad-like digits; these were probably made by inoffensive, herbivorous ornithopods. Something like an *Iguanodon*, although the age is wrong! On the other hand, another group is characterised by large, but relatively narrower prints with more slender digit imprints and quite distinct padding, and distinct claw marks. These are the hunters, the carnivores, and are representative of the theropods (the relatives of *T. rex*). Finally we have the smaller ones, which we think may have been made by both theropods and herbivores. It is not a simple matter to assign a maker!





Field examples

Let's have a look at a few of these in the field. This is our longest trackway (Fig. 7, *overleaf*). It is a very well known trackway in Scalby Bay, known as the Jackson Bay trackway. This type of print is that of a typical herbivore and, although the prints are very faint, it is still possible to measure the distances between them. From these measurements we can work out the stride and, using the size of the print, determine its probable speed of locomotion. To calculate the speed an approximation of the hip height of the animal is needed, and a general rule of thumb is that the hip height is equal to 4× the foot length. Notice also the fairly straight line of the prints. These animals did not walk like the sprawling Crystal Palace reconstructions, but walked with their legs underneath them and their limbs directed downwards. In other words they moved with an erect (rather than with a sprawling) gait.

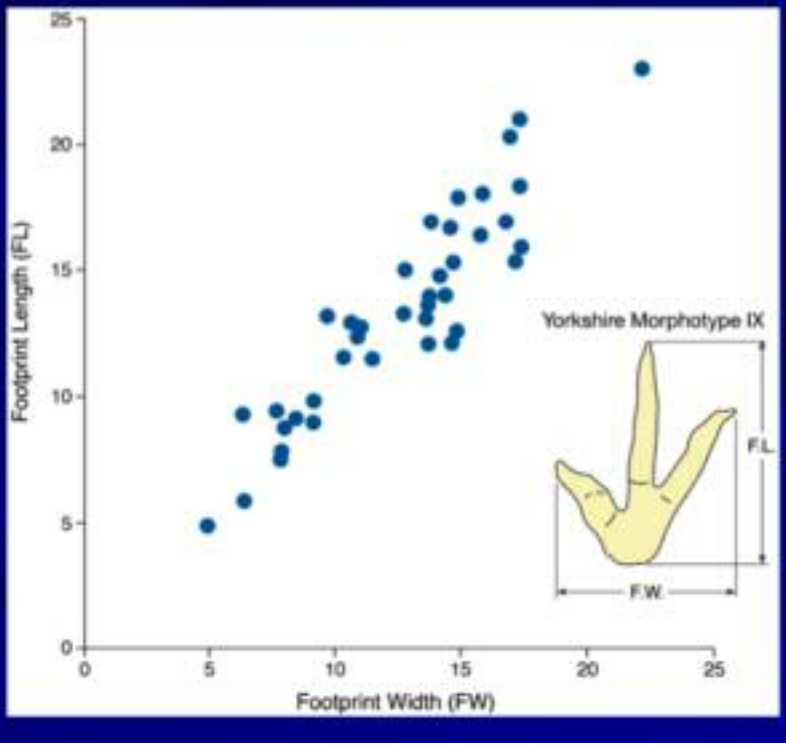
The first print that we found on the east coast, just south of Scarborough, still remains one of our best examples (Fig. 8, *overleaf*). The individual padded digit imprints are clear, with toe and claw drag marks. The transmitted features are beautifully preserved, and on the other side of the slab it is possible to demonstrate the depth to which the foot was impressed in the sediment, and thus determine the state of the sediment at the time. There was so much information to be deduced from this single specimen in terms of preservation and original foot morphology.

Once our database had reached a significant size we began to plot track length against track width (as representative of foot length against foot width) in an attempt to determine ontogenetic growth curves (Fig. 8). But one of the enigmas that constantly emerged was the lack of small prints. Why were there no small ones, or with some morphotypes, very few? Was it because small dinosaurs did not leave small prints, or was it because small dinosaurs lived elsewhere? To us it was clear that the former was not true, as there are many small delicate prints present that were left by small invertebrates — such as the xiphosurids, relatives of the present-day King Crab (*Limulus*). If small, light, arthropods could leave tracks, then surely 'baby' dinosaurs could! Another apparent anomaly is the absence of tail drag marks. Assuming the dinosaurs possessed tails, the only conclusion is that they did indeed spend much of the time with their tails uplifted — much as they are depicted in the film *Jurassic Park* and in the TV series *Walking with Dinosaurs*.

Then there is the second group (Group A), the big tracks — the quadrupeds. The first time these tracks were recorded was in 1999. Why was it so late after the first records of tridactyl tracks in the early 1900s? In our case the reason was simple but embarrassing: many of the tracks were so big that we did not notice them. For example, some of the transmitted tracks are more than 1m across. However, once they were recognised and digit imprints identified, it was clear that they were made by sauropods. Differences between the prints indicate that there were at least two types of sauropod responsible for the tracks. Well-preserved manus and pes prints have provided information on the foot morphology of sauropods (shape and digit details), while deeply incised prints have yielded striations down the sides

Fig. 7

Fig. 8


Footprint Length (FL)
Footprint Width (FW)
0
5
10
15
20
25
Yorkshire Morphotype IX
F.L.
F.W.

of the print that record entry and extraction (limb dynamics) within the sediment (Fig. 9). Rare examples have also recently been found of imprints of the skin ornament — small interlocking polygonal plates or scales on the base of the manus.

At some levels we come across areas where the sandstone beds are churned up — a result of the trampling of animals in a saturated sediment. American palaeontologists coined the term 'dinoturbation' to describe this feature. There is little doubt as to its origin, as the outline of a single limb (manus or pes) or digit imprints can occasionally be made out. In the field, the characteristic features of these beds are their flat tops and very irregular bases. From a purely sedimentological viewpoint the latter look like load structures (non-biological). In fact, over the years, a number of features in these beds have been given a sedimentological origin (such as water-escape features), while we could well offer a biogenic (dinosaur) origin.

The story of *brodricki*

It was a print from this Group A that provided us with our first significant story. It is the first new trace fossil ichnotaxon described from the Cleveland Basin, and even appeared on television some years back (Fig. 10, *overleaf*). The pes print is triangular in outline (hence the name *Deltapodus*), a three-toed foot with a prominent posterior pad. The manus print is crescent-shaped in outline with no clear digit imprints except for an inward-pointing first digit. We first identified the maker of this print as 'possibly' a sauropod, although there were some disturbing characteristics that did not quite fit this interpretation. Three publications later and we finally went for a stegosaur origin. At the time, this print was not recognised outside the Cleveland Basin, but more recently it has been found in Spain, Portugal, the U.S.A. and possibly Morocco — a truly cosmopolitan ichnogenus (whatever the maker!). We gave it the ichospecific name *brodricki*, after Harold Brodrick who first described dinosaur prints from Yorkshire.

The last category, Group C, were the swimmers. The characteristics of these prints have already been mentioned: parallel markings (commonly three) that represent the drag marks of the digits through the sediment. Our classic example of this category is from a slab near Whitby, where we were able to unravel a scenario involving swimming tracks and walking tracks on the same slab (Fig. 11, *overleaf*). The story involved animals walking over a damp substrate before a crevasse-splay inundated the area and animals swimming 'for their lives' in the swift flowing current. We know how deep the water was, how fast it was flowing, the size of the animals and which way they were swimming — all done with sedimentology and ichnology!

Dinosaur communities

So, are we in a position to be able to say anything meaningful about dinosaur community structure during the Middle Jurassic of the Cleveland Basin of Yorkshire? Although it is

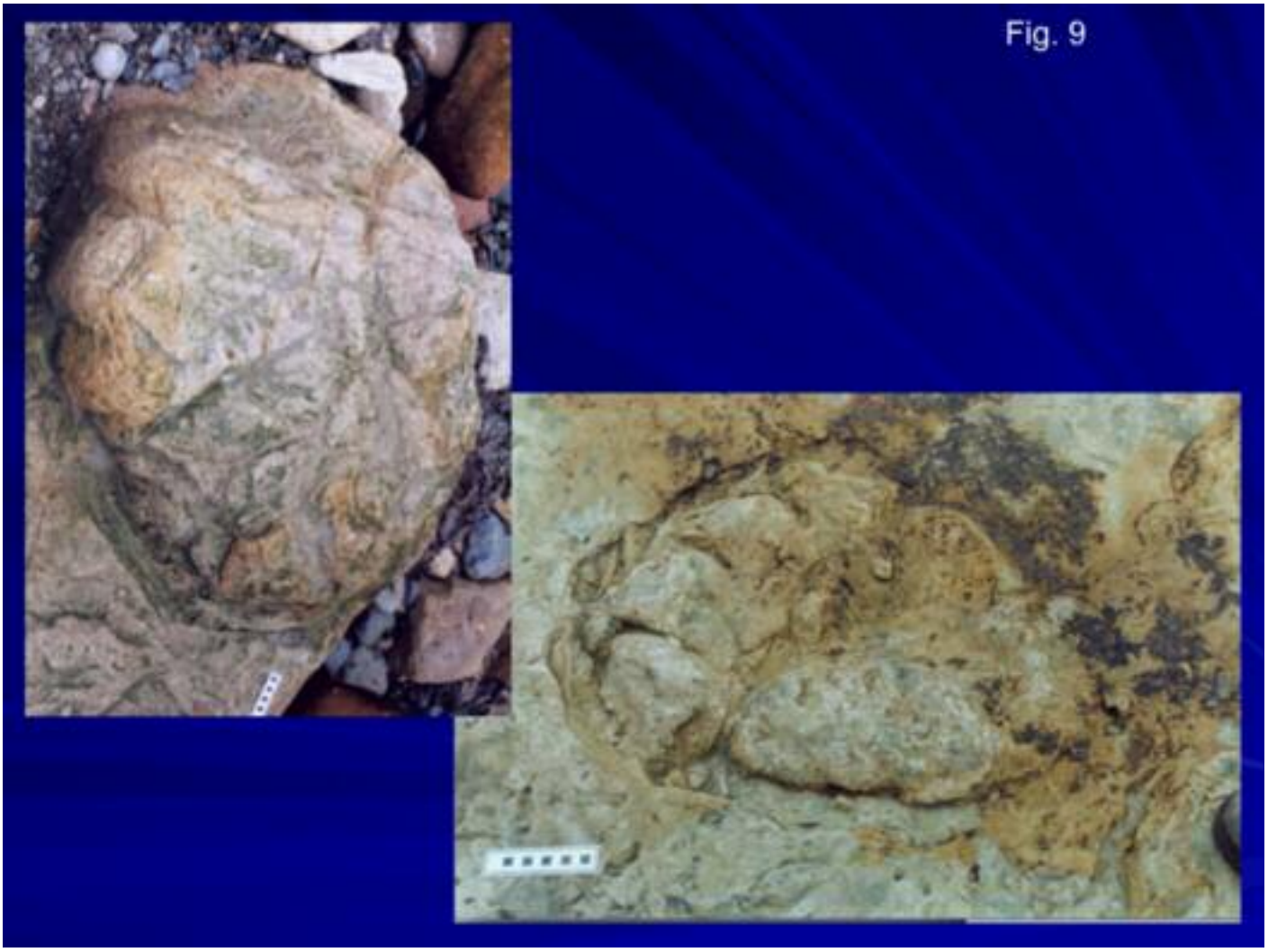
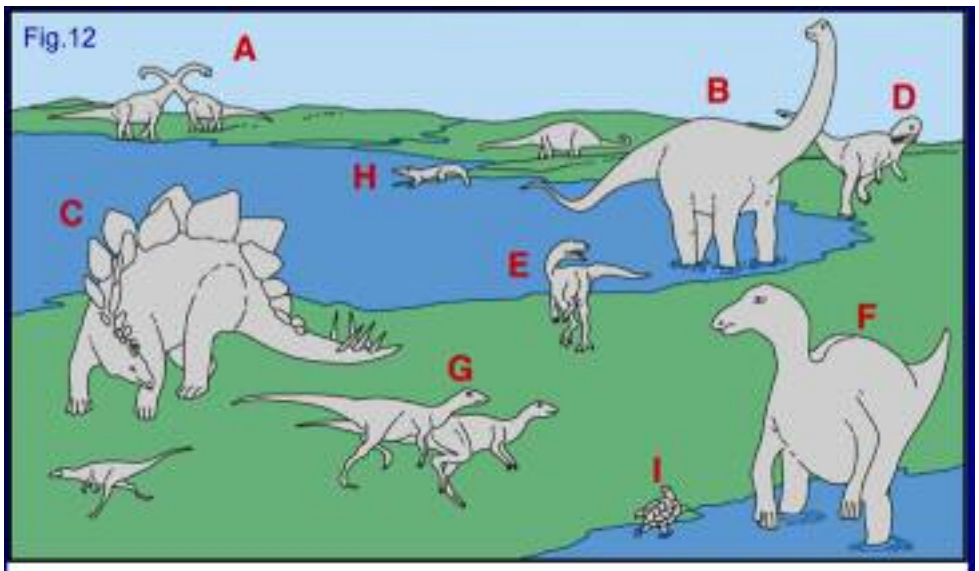


Fig. 10

Fig. 11

very difficult to positively identify the maker of the prints, or the numbers of individuals involved, it is possible to tentatively reconstruct a likely scenario. Our panorama shows two types of sauropod (Fig. 12): a large, inoffensive herbivore and a large, offensive carnivore; big and small tridactyls; the stegosaur *Deltapodus*; chelonians (fresh water turtles) and crocodiles. That is just the vertebrates! We can add to the food chain with invertebrates (mainly from the traces) and the all-important plants (gingkos, cycads, ferns, horsetails).

Finally, to improve our understanding of print preservation and interpretation we and our research students have investigated prints of modern ratites (emus) and undertaken print simulation in the laboratory. The feet of emus provide an excellent modern analogy to dinosaur feet and we have been able to use the limb dynamics and details of print morphology of these birds to interpret the structures we see in the Middle Jurassic rocks of Yorkshire (Fig. 13). One of our research students completed a whole sequence of experiments using laminated sediment and then impinging 'home-made' dinosaur feet in them. This has enabled us to interpret the shapes of fossil dinosaur tracks and try to determine the state of the sediment on which the animal moved.



Panorama showing possible dinosaur community that inhabited the Cleveland Basin during the Middle Jurrasic. Representatives of the following groups of dinosaurs are included: sauropods (two types; A and B), stegosaurid (C), theropods (two types; D and E), ornithopods (two types; F and G). Also included are examples of a crocodilian (H) and a chelonian (I).

Conclusion

Despite the advances made in the study of dinosaur prints from the Middle Jurassic of the Cleveland Basin, there is still much to be done. We still do not have a clear picture of dinosaur ecology or ontogeny in the Cleveland Basin, and until we find the elusive dinosaur eggs, nests or juveniles we never shall!

Book review

Stratigraphical charts of the United Kingdom: northern and southern Britain 2008 (ISBN 978-0-75183-561-8; wall charts, £8.43 + VAT each)

If you have space to spread out or stick up these charts (they are 85cm x 112cm each) you will find them extremely stimulating. They cover not only the large island of Britain with its offshore islands and Northern Ireland, but also the submarine areas from way north of Shetland to way south west of the Isles of Scilly. They would be even more informative if they covered the rest of Ireland and adjacent regions of France and the Low Countries, areas that are part of the same geological region. The charts show the evolution of the environments in which the rocks of Britain were formed by means of 28 lithostratigraphical columns.

The time scales vary: on the southern sheet 1cm represents 400Ma before 1000Ma, 50Ma to the end of the Proterozoic, 10Ma to a little way into the Pliocene, and 0.5Ma for the bulk of the Quaternary; on the northern sheet there is an extra scale of 20Ma beginning at 700Ma, to deal adequately with the Dalradian.

The varying scales make it possible to display the vast range of British rocks from the Lewisian Gneiss onwards; and it is rather awesome that from *c.* 1200Ma the only gap in the total record is that between the close of the Moine Supergroup *c.* 860Ma and the first formations of the Dalradian Supergroup *c.* 740Ma. Within each column there are gaps, of course, and this makes one wonder why. Was there no deposition, or subsequent erosion?

Most striking is the use of 12 colours to represent the dominant environment of deposition, plus three for extrusive igneous and one for metamorphic rocks. This shows that the same depositional environments recurred several times, and also reveals the lateral extent of depositional environments at any one time — e.g. shallow marine carbonate or calcareous mudstone in the areas called 'South Wales' and 'Bristol–Gloucester', while pelagic and hemipelagic in the adjacent 'Celtic Sea–Bristol Channel' and 'South-west England' areas.

There are useful symbols for key characteristics of the units, such as the presence of significant coal or evaporite deposits, major palaeosols, chert/flint, bioherms; and indications of major intrusive magmatism and orogenic events. Perhaps inevitably, in such a richly varied area as Britain, the columns cover areas that are too large, so that oddities appear. If you go south on the A470 from Builth Wells to Brecon you indeed traverse the "shallow marine siliciclastic" units of the (newly named) Aberedw and Cae'r Mynach Formations; but passing onto the "alluvial fans, fluviatile" Lower Old Red Sandstone Group you are not on the Milford Haven Subgroup, but on the Downton and then the Ditton Subgroups — which appear only on the Bristol-Gloucester and West Midlands columns. You need a different part of 'South Wales' to find the Milford Haven Subgroup; and no doubt similar contractions occur in every column. But this is a minor fault. The cartography (by P. Lappage of BGS) is so ingenious that you need not lose the period or epoch as you track across the charts.

— Philip Clark, MA, BSc Hons (Open), Dip Mus (Open)

Book review

Simpson, I. M. and Broadhurst, F. M.* 2008 *A Building Stones Guide to Central Manchester*. The Manchester Geological Association (no ISBN — private publication funded by Manchester Geological Association; paperback, 45pp; £5; contact secretary@mangeolassoc.org.uk)

Soon after receiving this book, I had the chance to accompany Dr Broadhurst and members of the OUGS on a tour using parts of two of the walks in the guide — a welcome 'road-test'.

The appearance of the book is outstanding: the front cover shows the splendid use of Carboniferous sandstones in Manchester Town Hall and the back cover shows the multi-coloured sandstones used in St Ann's Church, St Ann's Square. Much has been made in the press of the unsuitable use of replacement stone in these buildings, but here the mellow tones of the sandstones of Carboniferous to Permian age work well together. Centre folds continue with high-quality colour images of 30 relevant buildings, stone surfaces and two field localities.

I would have liked to see examples of a few photomicrographs too, but that is a small point. Where this guide scores over other similar publications is its precise use of maps for the four walks, with routes clearly marked in yellow. The authors make the book accessible to all readers by offering a useful, concise glossary of terms. I particularly liked the emphasis of building names and addresses in bold type, and the rock names in UPPER CASE.

Simpson and Broadhurst published one of the first building stones guides to Manchester in 1975, which that doyen of building stones writers Eric Robinson commended highly in his London guides — so this update is very welcome.

If you are visiting Manchester and know nothing about geology, I urge you to buy this book. If you are a geoscientist of any level of experience and want a clear text showing stones of many types and of widely differing provenances, I urge you to buy this book. If you are just interested in the cityscapes around us, yes, you've got it in this book too.

I took my first faltering steps in geology 40 years ago in a school in Bury (brilliantly taught too!) and would have loved a book like this showing the riches of the built environment just nine miles to the south.

— Tony Grindrod, OU Summer School Tutor

* Since this review was initially prepared we have heard the very sad news that Fred Broadhurst has passed away. He made an enormous contribution to our knowledge of north-west geology and was able to communicate his enthusiasm to students of all ages and backgrounds. One of the most charismatic of his generation of geologists, and a real gentleman. Fred will be sorely missed.

The Ebb and flow of the Yorkshire margins of the last British ice sheet

Dr Mark D. Bateman (Geography Department, University of Sheffield)

During the Late Devensian there were ice sheets around Yorkshire on three sides, and what was not covered with ice was largely submerged under pro-glacial lakes, e.g. Lake Humber (Fig. 1). The nature and timing of the Late Devensian ice sheet's dynamics, coming off the Dales and Pennines, down the Vale of York and down the present-day East Yorkshire coast, has been the subject of considerable research over the years. Their nature and timing are still debated.

In the Vale of York, maximal Late Devensian ice sheet limits have been advocated both at the York-Escrick moraine complex and at a more southerly line around Wroot and Thorne in the Humberhead Levels. These conclusions have implications for the formation and duration of the extensive pro-glacial Lake Humber.

Lake Humber is the largest single feature beyond the ice sheet in any model of Late Devensian Britain. The Late Devensian may have been a short-lived surge, but this conclusion remains disputed because there is a dearth of glacial diamict found south of Escrick, and because it is disputed whether the gravels at Wroot-Thorne are glacio-fluvial in origin. Recent work at Ferrybridge found a buried glacial diamict with sandstone erratics that is interpreted as having been derived by Vale of York ice, despite being *c.* 20km south of the Escrick moraine (Bateman *et al.* 2008). This material has been luminescence dated between 23,300 and 20,500 years ago.

Ice definitely came through the Humber Gap, as shown by the Horkstow moraine and by deposits exposed on the Humber foreshore at North Ferriby. There are two tills on the Holderness coastline — at Skipsea and at Withernsea — each with different erratic suites that indicate Lake District and Scandinavian origins. Both have been attributed to either a 'two-tier' glacier or to glacial surges from the North Sea. Both tills were deposited between *c.* 21,900 and 15,500 years BP. New work has found intact chironomidea in sands laid down between the two tills. Their presence suggests that there was an ice-free period between the depositions of the two tills, and that they therefore must represent two glacial advances. Luminescence dating of the chironomidea-bearing sand indicates that this ice-free period occurred 16,200 years ago.

What is clear is that more recent work shows that ice can move and respond to climatic changes more rapidly than was previously thought. Thus ice on what is now the Holderness coastline and in the Vale of York may have been dynamic, with more than one advance and retreat. What is also clear is that within the Late Devensian, and in particular in the Dimlingtom Stadial, ice may have existed in Yorkshire as late as *c.* 16,000 years ago. This conclusion agrees not only with contemporaneous ice re-advances elsewhere in Britain (e.g. in the Irish Sea basin, called the Killiard Point Re-advance, and in Scotland, called the Perth Re-advance), but also with ice re-advances of the neighbouring Fenno-Scandinavian ice sheet. All of these ice advances coincide with a recorded global climatic perturbation designated the Heinrich Event 1.

Thus the ice advances and retreats in Yorkshire may have been a response not just to regional conditions, but also to changes affecting the entire British ice sheet.

References

Bateman, M. D., Buckland, P. C., Chase, B., Frederick, C. D. and Gaunt, G. D. 2008 'The Late-Devensian pro-glacial Lake Humber: new evidence from littoral deposits at Ferrybridge, Yorkshire, England'. *Boreas* **37**, 195–210

Clark, C. D., Evans, D. J. A., Khatwa, A., Bradwell, T., Jordan, C. J., March, S. H., Mitchell, W. A. and Bateman, M. D. 2004 'Glacial maps of Britain and GIS database'. *Boreas* **33**

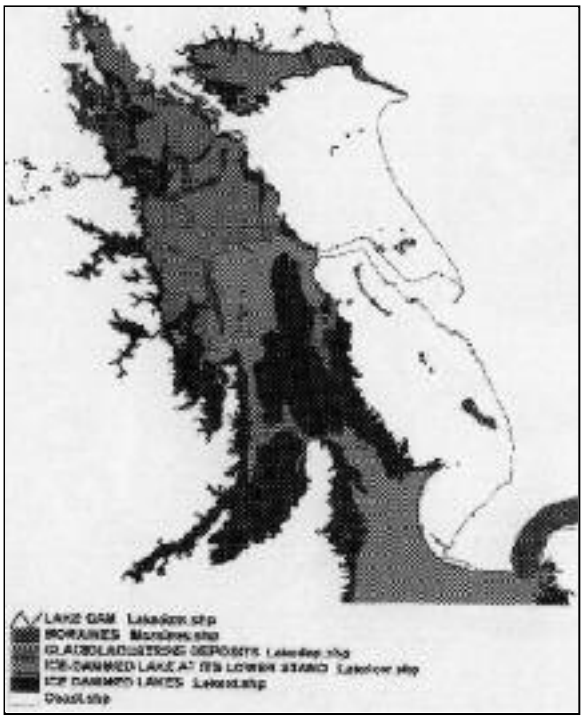


Figure 1 Extract from BRITICE database showing pro-glacial Lakes Humber and Pickering along with moraines found in the Vale of York and east of the Wolds (Clark et al. *2004).*

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Book review

Gill, R. 2010 *Igneous Rocks and Processes: a Practical Guide*. Oxford: Wiley-Blackwell (ISBN 978-1-4443-3065-6; 428pp; paperback £34.95, hardback £75.00)

The author declares in his preface that the book grew from teaching a second-year igneous petrology course at Royal Holloway, University of London. The publishers indicate that they see the book as a conventional course textbook and practical laboratory manual for introductory- and intermediate-level courses in igneous petrology. In reviewing the book I consider that this would be an excellent text for the ambitious first-year student, indispensable to a second-year student and still of value as a lead to the original literature in the final year of a BSc, MSci or MRes Geoscience course. Open University students working through S276/S278/S339/SXR260 and SXR339 would find this a valuable adjunct to their existing course resources. OU students who have completed S260/S236/S23/S278 and S333/S335 would also find much herein to update their knowledge.

The book follows a logical progression through the compositional spectrum of igneous rocks, starting with the 'simplest', most abundant, least-fractionated basaltic rocks (Chapter 2). We meet the gabbroic rocks in Chapter 4 and the ultramafics in Chapter 5. Chapter 6 covers the andesites, dacites and rhyolites, while Chapter 8 covers the granitic rocks. Finally, the mysterious world of the alkali rocks is admirably discussed in Chapter 9. In all cases Robin Gill follows a laudable philosophy, through observation and description, through interpretation of processes and concludes with a consideration of the environment of crystallisation, both in plate tectonic and in pressure/temperature and volatile domains.

Gill also includes stand-alone chapters: Chapter 1, where he takes the confusion out of igneous rock nomenclature; Chapter 2, where he describes basaltic rocks; and Chapter 3, a brilliant exposition of magmatic differentiation. Phase diagrams are often a 'tearful experience' for students — I used to look back at an old OU video by John Wright to take the mystery away, but now Gill gives a masterly treatment of binary and ternary systems. In Chapter 7, he looks at how magmas erupt — an introduction to pyroclastic processes and products (a topical issue in view of the recent eruptions in Iceland producing volcanic ash).

Throughout the book the author resorts to the strategy of using boxes to address problematical or contentious, difficult issues. For example, in Chapter 2 we have a refresher on the structure and composition of pyroxenes (Box 2.1). In Box 2.2 he addresses how to distinguish olivine from augite in thin section. The boxes are an answer to a student's prayer, often providing a time-saving strategy for short essays. In fact, I expect to see the content of the boxes copied word for word in essays for years to come!

Line drawings are of exceptional quality throughout the book and the black and white photographs are usually well reproduced, a rarity in many modern textbooks. Dr Gill also provides us with superb colour photographs and photomicrographs in a central 32-page spread; the images and a colour correct Michel Levy chart are referenced to the appropriate chapters.

In every chapter Gill finishes by reviewing key points and challenges us with a series of exercises (answers kindly provided at the end of the book). The book concludes with three appendices:

Mineral identification using a petrological microscope
Petrographic calculations
Symbols, units and constants used in this book

The volume has an excellent glossary, and an 18-page bibliography with all the references I would have expected. The most recent reference is from 2008, which is a remarkable feat in itself bearing in mind the protracted publication process for a book of this length. Finally, there is a carefully compiled index.

The publisher highlights a companion website: www.wiley.com/go/gill/igneous

Unusually, this site works, and gives easy access to full-screen line drawings and tables.

A really excellent textbook. In preparing this review I re-evaluated the competition: textbooks like Wilson 1989, Hall, 1996, Best and Christiansen 2001 and even Cox, Bell and Pankhurst from way back in 1979 — in short, the books used on many courses in North America and Europe.

I would have no hesitation in recommending this volume by Robin Gill as a great buy for anyone embarking on a geoscience degree course, for experienced igneous petrologists needing an update, and also for specialists in other geoscience fields who habitually through work or leisure find themselves passing through Hawaii, Oman, Sicily or other igneous places, as one does in our wonderful subject.

My only regret as I read this book was: Why, oh why was a book of this scope, clarity and quality not available in my undergraduate years?

— Tony Grindrod, OU Summer School Tutor

Palaeoclimate modeling: the past as a guide to the future

Dr Alan M. Haywood (School of Earth and Environment, University of Leeds)

Numerical models of the Earth's climate system are the only tools we have to predict the global- and regional-scale impacts of human-induced global warming. The entire process of assessing risk, calculating impacts and developing mitigation strategies is ultimately based on the outputs from these models. Yet a model, as any definition from a dictionary will quickly tell you, is a simplified representation of a more complex system: in this case the climate system.

Climate models were not developed for the sole purpose of determining the planet's climate in the year 2100. They were developed to help us understand and appreciate what we do not know about how climate works. Climate model predictions are evaluated against observational datasets of current climate. Much of this observational data is 'in-sample', meaning that it has been used initially to evaluate, then to tune climate models to reproduce observed climate as far as it is reasonable to do so. Therefore, such comparisons can, in certain circumstances, tell us surprisingly little about the predictive capabilities of climate models.

In contrast, the study of Earth history provides a unique natural laboratory in which to evaluate climate models rigorously.

This talk focuses on climate model simulations for greenhouse climates of the Late Cretaceous, the Paleocene-Eocene Thermal Maximum and the mid-Pliocene warm period. It uses the scientific principle of Occam's Razor* to discuss the efficacy of climate models in reproducing past climate change.

In palaeoclimate research an added complication is introduced: the efficacy of the geological data itself. In the past, climate models have largely not fared well when a data/model inconstancy has been identified. In other words, it has normally been the case that the 'problem' has been attributed to the model and to the data, or to faulty interpretation of the data. This is no longer the case, however, and examples of where the models highlight uncertainty in the data are presented.

The significance of these results concerning the robustness of climate models in reproducing drastically different past climate states is placed in the context of what models currently predict for the future.

* Entities should not be multiplied unnecessarily.

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Book review

Schreiber, B. C., Lugli, S. and Babel, M. (eds) 2007 *Evaporites Through Space and Time*. London: Geological Society Special Publ 285 (ISBN 978-1-862392-32-8; hardback, 373pp; £85)

The evidence we find on our OU field visits to the Permian of County Durham always suggests that there might be more to evaporites than a straightforward sequence of salts. Yet evaporites are often widely regarded as products of a narrow and predictable range of depositional environments. This Geological Society Special Publication reveals evaporites' remarkable diversity in the geological record and the significant role they play in unravelling Earth's history.

Originating from the 2004 International Geological Union conference in Florence, this book brings together the work of geologists from many countries and with many different research interests. A useful overview of key themes and the addition of material not presented at the conference nevertheless produce a comprehensive and coherent volume.

The publication is divided into sections covering tectonics and basin evolution, depositional models, post-depositional evolution of evaporites and ancient basins, concluding with regional reviews of the Ukraine and of the Permian Basin of West Texas and New Mexico. The editors also look ahead briefly to future research, for example, the role of rift-sourced hydrothermal fluids in evaporite formation and extraterrestrial deposits such as Martian evaporites.

In the tectonics and basin analysis section, evaporites are used to unravel the tectonic development of the South Atlantic between West Africa and Brazil. Three-dimensional seismic analysis is used to examine submarine channel-mouth lobes in the Messinian (Late Miocene) evaporite basin of the Eastern Mediterranean. Miocene evaporites are also considered in the context of oil reservoir formation in Iraq. In central Iran, potash-bearing evaporites are attributed to the influence of hydrothermal brines. A further paper describes a vast North African Late Triassic–Early Jurassic evaporite basin, and considers the tectonic and climatic factors affecting its formation.

Babel, one of the editors, presents conceptual models for evaporite formation in shallow salina-type basins and applies these to the interpretation of gypsum facies of the Middle Miocene evaporites of the Carpathian region. Laboratory evaporation of brines from Spain is used to determine the order of evaporite mineral precipitation.

Further papers consider post-depositional effects and explore evaporites in the Appenines, in Calabria, in the Carpathians and in the Polish Zechstein Basin. The existence of Neoarchaean evaporites is inferred from disruption in carbonates in South Africa.

As with all such Geological Society publications, the volume is highly specialised, but the useful introduction and abundant high-quality figures and images help to make it more accessible to the non-specialist reader. Sadly, the Permian in North East England is not discussed. Time, perhaps, for someone to take a closer look?

— Caroline Peters, BSc (Hons) Geoscience (Open)

Book review

Nichols, Gary 2009 *Sedimentology and Stratigraphy* (2 edn). London: John Wiley & Sons (ISBN 978-1-4051-9379-5; 419 pages, £60)

This book has been written to be accessible to those studying at undergraduate level, but develops the subject matter considerably further.

The presentation style will be instantly familiar to those with any experience of Open University course texts, where each new concept appears as a sectioned item and terms are emboldened in their first occurrence. In addition to the subject matter of the title the text provides ample background on mineral properties, composition, identification in thin section and mineral alteration during weathering. Essentially a large section is also devoted to physical descriptions of sediments and as such this is a valuable accompaniment to the OU S276 Geology course currently being studied by this reviewer. As the title indicates, the early chapters take a somewhat cyclical journey through the processes of sediment sources, generation, transport and deposition, and recycling, with many clear figures, diagrams and photographs, which put these processes into clear context in the field.

The middle section then provides highly detailed, yet readily accessible, descriptions of depositional environments: aeolian, rivers, marine and lake settings, where as well as particulate sediments the formation of sediments by, for example, carbonate deposition is also thoroughly considered.

It is, however, in the final chapters — in which post-depositional sediment alterations are considered, particularly under the influences of living organisms and in turn the influence of sedimentation on living organisms — that the other objective of the book is manifest, namely, interpretation of the fingerprints left in sediments over the past few million years by environmental processes, consideration of recent partial fingerprints and how those can be used as predictors for the possible environmental trends in the near future.

The text is accompanied by a CD of images and diagrams and while many are simply larger, colour versions of those printed with the text, these are of sufficient value, and alongside additional images are worth perusing. However, the images are delivered as a series of chapter-related folders — with a little additional effort these could have been presented in a more accessible web browser format.

In summary, this is a valuable text for OU students at level 2, but perhaps too in-depth, and the real value would be afforded to those progressing to related level 3 courses and beyond.

— Chris Popham, S276 Geology student

Enter the Anthropocene: an Epoch of time characterised by humans

Dr Mark Williams[1, 2] and Dr Jan Zalasiewicz[1] ([1] Department of Geology, University of Leicester, Leicester LE1 7RH, UK; [2] British Geological Survey, Keyworth, Nottingham)

Abstract

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change suggests changes to water supply, ecosystems, biodiversity, food supply, coastal regions and human health based on a 1˚C to 5˚C change in global climate. Changes to the life support system of planet Earth become profound beyond a 2˚C mean rise in global temperature, well within the envelope of global warming predicted for the 21st century.

With a greater rise in global temperature 'significant extinctions' are anticipated on a scale that has not occurred for millions of years. In this context it is vital that we establish the rate and degree of present environmental change and set that against similar fundamental changes in the past.

To this end, the concept of an Anthropocene Epoch of geological time, first conceptualised by the Nobel winning scientist Paul Crutzen, forms an excellent and readily accessible medium for assessing the degree of environmental change caused by humans.

Introduction

In the early years of the 21st century men and women went to and fro over this globe about their little affairs, serene in their assurance of their empire over matter. Our technology, seemingly so advanced, looked able to deal with all of the problems confronting humanity. Few people regarded the natural powers of the Earth as vulnerable to our activities. And yet, across the vastness of geological time Earth viewed the actions of people with increasing despair. And slowly, but surely, she drew her plans against us …

We have written and adapted these words, using similar ideas and metaphors, from H. G. Wells' masterful late Victorian science fiction novel *The War of Worlds*. Wells' carefully crafted opening salvo to his novel contains words prescient in the early 21st century as we face the prospect of rapid change to our climate, and warns us about complacency in the belief of our dominion over nature.

The eve of the Anthropocene

As early as the late 19th century, scientists were commenting on the extent of human influence on planet Earth. The Italian geologist Antonio Stoppani (1873) was perhaps the first to moot these ideas. Later, as the 19th century drew to a close, the Swede Arrhenius and the American Chamberlain worked out the relationship between the amount of CO_2 in the atmosphere and global warming. Arrhenius suggested that future generations of humans would need to raise surface temperatures to provide new areas of agricultural land and thus feed a growing population. But he could not have conceived of the massive rate of human population increase in the 20th century.

In the early 21st century the Nobel Prize-winning scientist Paul Crutzen (2002) resurrected the concept of the Anthropocene to denote the ever-increasing influence of humans on Earth. The word has now entered the scientific literature as a vivid expression of the degree of environmental change on planet Earth caused by humans (Zalasiewicz *et al.* 2008 and references therein).

For the Anthropocene to become useful, however, it needs some quantification. How might an Anthropocene Epoch be unique relative to the Holocene or the Pleistocene epochs that preceded it? What criteria could we use to quantify when the Anthropocene began, and how might future generations of geologists recognise its signal in the rock record? More importantly, though, does the term Anthropocene help us to understand the influence of humans on the present and future Earth?

How unique is the Anthropocene?

The use of tools was once thought to distinguish humans from all other animals, and indeed the earliest people who lived two million years ago in Africa are called *Homo habilis*, the 'handy man'. But the origins of human technology are deeper, revealed in the actions of our primate cousins fishing for termites with a twig, or breaking the shells of molluscs or nuts to find the original fast food. For a long time then, in fact for more than a million years, people have been modifying planet Earth. For much of that human story technology was little more than muscle and sinew, supplemented later by fire. Traces of humans in the Pleistocene rock record are therefore rare, and stay rare until the Holocene.

The influence of humans is felt more strongly towards the end of the Pleistocene Epoch with the demise of the so-called 'megafauna' that included the sabre-toothed cats in North America or the woolly mammoths of Siberia. On many continents the disappearance of the megafauna appears to coincide with the arrival of modern humans. Like many events in the geological record this extinction is diachronous — that is, it did not happen everywhere simultaneously: the megafauna disappeared in Australia 50,000 years ago, but in the Americas 13,000 years ago. Yet, the megafauna are still living in parts of Africa and south Asia, albeit now under threat nearly everywhere. From the beginning of the Holocene, about 11,000 years ago, there is more widespread evidence for human activities, with the rise of agriculture in the 'Fertile Crescent' of the Middle East, the Far East, and later in Mesoamerica and South America. This change of cultivation leaves a clear fossil record in the pollen preserved in sedimentary successions through this interval. And, the clearance of forests, associated with the rise of agriculture, may have begun to elevate CO_2 levels in the atmosphere, gradually from 260ppm to 280ppm long before the Industrial Revolution (Ruddiman 2003).

Following the Neolithic revolution of agriculture, humans began to live in villages and towns, and by the 3rd millennium BC the cities of ancient Mesopotamia, the Nile Valley and the Indus Basin of Pakistan were well established and culturally distinctive. Still later, urban cultures spread across the tropical and temperate zone everywhere, with those in Europe, central and South America, and China being diverse and advanced by the first millennium BC. This rate of urbanisation has accelerated through time, with the first million-strong cities possibly appearing in late medieval times, such as Angkor in Cambodia. By the 19th century London and Paris had clearly reached this size. Now there are many cities with between 10 and 20 million inhabitants, and the number of such populous cities continues to grow.

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Urbanisation is a direct result of a population explosion. Since 1800 global population has risen from roughly 1 billion, to 6.5 billion in 2000 and it is set to rise to a projected 9 billion by 2050. That population growth is linked with the Industrial Revolution that supplied the power and technology to feed those extra mouths. Cities, and especially megacities like Jakarta, Rio de Janeiro or Shanghai, are now the most visible expression of human influence on the planet (Fig. 1). The growth of cities is therefore a characteristic feature of the Anthropocene.

In 'terraforming' cities and building the dams and agricultural land that water and feed them, humans have wrought a roughly order of magnitude change in the long-term rate of erosion and sedimentation (Hooke 2000; Wilkinson 2005). Paradoxically, while deforestation and changes in land use have resulted in more sediment transported in rivers, many of those rivers are now dammed, preventing the flow of that sediment to continental shelves (Syvitski 2005). Such changes may be impermanent though. If human construction were to stop, nature would soon take over our constructions, reducing them to rubble over the millennia as she has done with the lost cities of ancient civilisations (Fig. 2). After 10,000 years, perhaps only a layer of concrete would remain.

More profound than our buildings may be the biological and chemical signals left by humans. Thus, enhanced dissolution of increased atmospheric CO_2 in the oceans is increasing their acidity. Significant drops in oceanic pH have already occurred. Further projected decreases will stress calcifying organisms such as corals or the marine plankton that form the base of many food chains, though the biological response is complex. Ocean acidification alone may substantially change marine ecosystems over the next century and thus contribute to the impoverishment of global biodiversity.

Figure 2 Angkor, Cambodia (August 2009). One of the four gates to the Bayon, Angkor Tom. In the 12th and 13th centuries Angkor was at its zenith, and may have housed more than a million people. Yet, when the temples of Angkor were 'rediscovered' and excavated in the 19th and 20th centuries, 500 years of neglect had reduced many to rubble, and Angkor appeared as the classic romantic 'lost city'. While human constructions will fall, the signal of chemical pollutants and radioactive waste that we have accumulated over the past 200 years will leave a signal that stretches into the distant future, and one that could be identified by geologists millions of years hence: thus identifying the Anthropocene as a permanent addition to the Earth's geological record.

The coming of the Anthropocene

The geological timescale of Earth spans some 4.5 billion years. This vastness of time encompasses the formation of our planet, the formation of the oceans and of all our continents, and the birth of life and the evolution of the biosphere to its present complexity. For utility the vastness of geological time is divided into more manageable packages that range from the almost unfathomably long (eons encompassing hundreds of millions or indeed billions of years such as the Phanerozoic or Proterozoic), through smaller (yet still enormous) packages of time, like the eras, that are characterised by a particular fossil record, perhaps most notably the dinosaurs and ammonites for the Mesozoic Era beginning about 250 million years ago and terminating about 66 million years ago. More fathomable for us as humans are periods of geological time, such as the Cambrian or Cretaceous. For these we can grapple with a distinctive rock record, like the chalk of the Cretaceous Period. Periods are divided further into epochs and ages, and the record of fossils in rocks that were deposited in these shorter intervals of time is now so well constrained that we can correlate rocks of precise age globally and reconstruct how our planet looked for a vast array of different time slices. The last period of time, the Quaternary, began just 2.6 million years ago, and has two epochs, the Pleistocene and the Holocene. The latter began only about 11,000 years ago, witnessed by changes in

Figure 1 (left) Shanghai, China (September 2007). In 1750 the city had a population of perhaps 50,000. Census data place the modern population at more than 16 million, making Shanghai, by some definitions, the largest city in the world. Shanghai is a classic example of the rapid emergence of megacities in the late 20th and early 21st centuries and is thus a vivid expression of the Anthropocene.

climate that are clearly seen and now formally defined in an ice core from Greenland (Walker *et al.* 2009). The Holocene is really just the last of a series of interglacial climate states that have punctuated the severe icehouse climate of the past two million years.

We may add to the Quaternary Period a third Epoch, the Anthropocene, but then we need to ask the question of when this Epoch began and how does it differ from previous geological time units?

The geological timescale that we use to subdivide the expanse of Earth history has been evolving its form for more than two hundred years, beginning with the realisation of the enormity of geological time encapsulated in Hutton's unconformities. Many of the periods of geological time, like the Ordovician, the Carboniferous or the Jurassic have been recognised for more than one hundred years, and although their boundaries and precise definition are often still argued over, most divisions are drawn at fundamental changes in fossil animals and plants recognised in the rock record.

Nowadays, when a chronostratigraphical boundary is defined, it is marked by a 'golden spike', more technically known as a Global Stratotype Section and Point (a GSSP). This is usually placed at some major event, most notably a large and sudden turnover in fossil biota, though sometimes chemical markers are used. When stratigraphical boundaries first began to be identified in the 19th century, little was known about the causes of major animal and plant extinctions, and still less was known about the enormous climatic changes reflected in the geological rock record. Only much later, indeed in the latter part of the 20th century, was the geological timescale seen to reflect fundamental changes in the Earth's climate state. This realisation came about largely through the work of the Ocean Drilling Programme that recovered sedimentary cores from the sea floor worldwide. Once the stratigraphy of these cores was carefully reconstructed, and once correlated around the world, they showed a precise record of climate change locked in chemical signals recovered from marine microfossils. For example, with the exception of the Cretaceous–Palaeogene boundary, fundamental climate change is implicated in all of the period and epoch boundaries of the Cenozoic Era (Zachos *et al.* 2001). Thus, the Eocene–Oligocene boundary coincides with major ice sheet growth on Antarctica, while the Neogene–Quaternary boundary marks a fundamental change to high-frequency orbital-modulated glacial-interglacial oscillation that has characterised the past 2.6 million years.

Can we recognise a fundamental event, such as a change in climate, to diagnose an Anthropocene Epoch? We know from the geological, archaeological and observed record that climate change happens naturally (Zalasiewicz and Williams 2009). These natural changes may cover enormous expanses of time, such as long-term global cooling through the Ordovician Period or through the Cenozoic Era, controlled by geological processes of long duration, such as evolving continental configurations and their influence on ocean and atmosphere circulation, the building of mountain chains, or long-term changes in atmospheric composition. Dramatic and rapid changes in climate also happen naturally, such as the Paleocene–Eocene thermal maximum of 55 million years ago, apparently associated with the rapid — at least on a geological timeframe — release of carbon to the atmosphere and associated global warming. Even more rapid climate change is associated with the actions of volcanic eruptions. Thus, the eruption of Tambora in 1815 on the island of Flores in east Indonesia threw more than 50 cubic kilometres of volcanic ash into the atmosphere that in 1816 caused 'the year without a summer'. The lower surface temperatures caused by the 'global dimming' effect of vast amounts of ash in the upper atmosphere caused widespread crop failures and famine in Europe and North America during 1816 (Oppenheimer 2003).

Changes to atmospheric greenhouse gas composition since the beginning of the Industrial Revolution, and in particular the rapid rise of pCO_2 during the last 50 years, is unprecedented. Atmospheric CO_2 levels, now more than 380ppm, are much higher than pre-industrial levels of 280ppm, higher than for the past three million years, and lie well outside the envelope of CO_2 change associated with the glacial-interglacial oscillations of the Pleistocene. This change in atmospheric greenhouse gases is recorded in both Greenland and Antarctic ice cores, locked in gas bubbles trapped in snow that fell over the past 200 years to form the ice. This change in CO_2, showing a rapid climb from the early 19th century, forms one potential criterion by which to define the base of the Anthropocene and is globally correlative: the base of the Holocene Epoch is similarly defined by climate change recognised in the NGRIP ice core of Greenland (Walker *et al.* 2009). The rise in atmospheric pCO_2 is directly linked to an increase in global surface temperature and to a commensurate range of regional climatic effects. In some regions, most notably the Antarctic Peninsula (Fig. 3) surface temperatures have risen dramatically in the past 50 years.

Figure 3 British Antarctic Survey field-camp 'Romeo 2', January 2006, James Ross Island, northern Antarctic Peninsula. This BAS field-team collected fossil material from rocks representing the warm Early Pliocene as an analogue for future climate warming in this region. The Antarctic Peninsula has seen surface temperatures rise rapidly since the 1950s (photographed by Mark Williams).

While human-induced climate change is clearly a feature of at least the past 200 years, many other features of human environmental modification may provide an equally good or indeed better definition for establishing the boundary between the Holocene and Anthropocene. For example, we might look for chemical signals of the Anthropocene, associated with the first metal smelting, or with the invention of a range of man-made products

including plastics that have left a distinctive and global trace in sediments. We might even take the atom bomb tests of the 1940s and 1950s, the by-products of which are radiogenic isotopes of plutonium, americium, strontium and caesium that leave a global and extremely long-term record. These, in particular, provide a tie with the acceleration of pCO_2 rise in the atmosphere since the 1940s and with the increasing globalisation of the late 20th century (see Steffen *et al.* 2007). They also enable us to define a 'golden spike' in an ice core or sedimentary succession that has accumulated through the past few hundred years, to signal a precise horizon that we can correlate globally that says, before this interval is the Holocene and after it is the Anthropocene.

Still, the changes we have seen so far may simply be the tip of an iceberg, and changes to biodiversity for the 21st century projected by the Intergovernmental Panel on Climate Change's 4th Assessment Report of 2007 look set to leave a striking, distinctive and permanent signal in the rock record. Like the late Precambrian metazoans of the fossil record that precede the main event of the Cambrian explosion of life, or the Permian extinctions that foretell the major Permo-Triassic boundary extinction, we may simply be in the run-up to the main event.

What might the Anthropocene tell us about the future?

The Anthropocene helps us to conceptualise that the sum effects of human activity are comparable to Epoch-defining changes of the geological past. As we write in December 2009, the governments of the world are meeting in Copenhagen to try and mitigate the effects of global warming caused by greenhouse gases. China, now the largest greenhouse gas contributor to the atmosphere, has a population four times that of the second greatest polluter, the USA, but a level of GDP per capita only one twentieth. If all people are to live with a western standard of lifestyle then something radical must happen to our technology, particularly with the way in which we generate energy. In *The War of the Worlds* H. G. Wells warned against complacency. In our discussion we have noted that the full scale of the Anthropocene may not yet have begun, that we may still be approaching its main 'event horizon'. The Anthropocene, thus, may well grow to greater scale. Even so, assessment of the current evidence suggests that we are already living within it. Its definition, be it marked by massive biodiversity decline, signals of chemical pollutants, radiogenic isotopes or a residue of concrete and bricks in the sedimentary rock record, is still to be debated, and may involve a combination of these factors. What we can envisage, is that geologists visiting our world in the distant future will see a geological boundary marked by fundamental changes as great as those that define, say the Paleocene-Eocene boundary, or of other geological boundaries that mark Earth's long and eventful history.

References

Arrhenius, S. 1896 'On the influence of carbonic acid in the air upon the temperature of the ground'. *London, Edinburgh, Dublin Philosoph Mag J Sci* **Ser 5, 41**, 237–75

Chamberlin, T. C. 1897 'A group of hypotheses bearing on climatic changes'. *J Geol* **5**, 653–83

Crutzen, P. J. 2002 'Geology of mankind'. *Nature* **415**, 23

Hooke, R. LeB. 2000 'On the history of humans as geomorphic agents'. *Geol* **28**, 843–6

Oppenheimer, C. 2003 'Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815'. *Prog Phys Geo*g, 230–59

Ruddiman, W. F. 2003 'The anthropogenic Greenhouse Era began thousands of years ago'. *Climate Change* **61**, 261–93

Steffen, W., Crutzen, P. J. and McNeill, J. R.. 2007 'The Anthropocene: are humans now overwhelming the great forces of Nature?'. *Ambio* **36**, 614–21

Stoppani, A. 1873 *Corsa di Geologia*. Milan

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J. and Green, P. 2005 'Impact of humans on the flux of terrestrial sediment to the global coastal ocean'. *Science* **308**, 376–80

Walker, M., Johnsen, S., Rasmussen, S. O., Steffensen, J. P., Popp, T., Gibbard, P., Hoek, W., Lowe, J., Björck, S., Cwynar, L., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D. J., Nakagawa, T., Newnham, R. and Schwander, J. 2009 'Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records'. *J Quat Sci* **24**, 3–17

Wilkinson, B. H. 2005 'Humans as geologic agents: a deep-time perspective'. *Geol* **33**, 161–4

Zachos, J., Pagani, M., Sloan, L., Ellen, T. and Billups, K. 2001 'Trends, rhythms and aberrations in global climate 65 Ma to present'. *Science* **292**, 686–93

Zalasiewicz, J. and Williams, M. 2009 'A geological history of climate change', *in* Letcher, T. (ed.), *Climate Change: Observed Impacts on Planet Earth*. Oxford: Elsevier, 127–43

Zalasiewicz, J., Williams, M , Smith, A., Barry, T. L., Bown, P. R., Rawson, P., Brenchley, P., Cantrill, D., Coe, A. E., Cope, J. C. W., Gale, A., Gibbard, P. L., Gregory, F. J., Hounslow, M., Knox, R., Powell, P., Waters, C., Marshall, J., Oates and Stone, P. 2008 'Are we now living in the Anthropocene?'. *GSA Today* **18**, 4–8

Volcano–ice interactions in Iceland

Dr Dave McGarvie (Staff Tutor, Open University)

A fortuitous combination of high latitude plus a regular supply of erupting basalt and rhyolite means Iceland is the best place on the planet to study volcano–ice interactions.

Sustained and localised eruptions into thick ice sheets produce steep-sided edifices called *tuyas* (Fig. 1). Pronounced vertical growth (up to 1500m) is a consequence of confinement by ice, as the volcanic pile uses less energy to grow vertically. Fissure eruptions into ice sheets produce long, linear ridges that are such distinctive features of the Icelandic landscape.

Although broad similarities exist between the products of Icelandic rhyolite and basaltic eruptions — key differences exist that provide insight into the complexities of volcano–ice interactions. These were explored and illustrated.

As stratovolcanoes, effusive rhyolite eruptions produce ridge-forming and perched lava flows (Fig. 2). Ridge-forming lavas flow within ice-walled canyons melted into ridge crests, where the ice is thinnest and lava pathways are easiest to melt. Perched lavas travel along the wall–ice junctions of valley glaciers. When the ice melts they are left 'perched' on valley walls.

Finally, studies that combine physical volcanology, geochemistry and Ar–Ar dating are gradually revealing the pattern of Icelandic rhyolite volcano–ice interactions during the Pleistocene, with some surprising results.

Figure 1 Tuya*: steep-sided rhyolitic edifice (a* tuya*) formed during a sustained rhyolitic eruption into thick ice. A late-stage lava cap overlies early erupted phreatomagmatic tephra. The minimum ice thickness during eruption is the top of the lava cap.*

Figure 2 Ridge-forming flow: a ridge-forming rhyolitic lava flow at an Icelandic stratovolcano. Such lava flow within ice-walled canyons and indicate a minimum ice thickness at the time of eruption. They also illustrate how thicker, flanking ice effectively confines flowing lava to ridge crests.

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Book review

Scarth, Alwyn 2009 *Vesuvius – A Biography*. Terra (ISBN 978-1-90354-425-9; hardback, 342pp; no price given)

When I was nine year old I was given *The Elements Rage*, a book of essays ranging from hurricanes to volcanoes by way of snow, meteorites and other 'violent manifestations of nature'. The chapter on volcanoes introduced me to Krakatoa, Mont Pelée, Paricutín and, of course, Vesuvius (which had just begun the 1944 eruptions when the book was being written — "it added considerably to the difficulties of A.M.G.O.T. [the Allied forces invading Italy] in looking after the civilian population in the area"). I am pleased to find that this old book still grips an intelligent lad of that same age. He is a bit young yet for Alwyn Scarth's detailed and enjoyable 'biography' of Vesuvius, but I might think of it for his, say, 15th birthday, especially if he has added an interest in some of the more entertaining byways of history and literature to being properly grabbed by 'violent manifestations of nature'.

'Biography' is a good choice for the sub-title. There is everything here you could ever want to know about Pliny the Elder and Pliny the Younger, about the obsessions of medieval monastic chroniclers, about the use of natural disasters in the policy of the Counter Reformation, and about the rediscovery of Pompeii and Herculaneum.

Particularly noteworthy are two successive chapters. The first is on Sir William Hamilton, British envoy to Naples from 1764 to 1800, complaisant husband of Emma. William was a pioneer volcanologist whose repeated field trips to Vesuvius, careful reading of Classical and earlier 18th-century authors, and reports to the Royal Society of London, made him "one of the founders of modern volcanology". "He maintained a humble modesty about the value of his own studies and he felt unable to develop a system or methodology about volcanoes", writes Scarth. "I shall content myself with collecting facts", wrote Hamilton, "and let who will form them into a system afterwards".

The next chapter is on "Vesuvius as a tourist attraction: the Grand Tour". Its text covers touring well into the 19th century, and includes quotations from such observant tourists as Shelley, Goethe, Sir Humphrey Davy, Hans Andersen, Charles Dickens and Mark Twain.

The last chapter on "The future: the eruption to be avoided" is a careful and worrying account of the likelihood that the scientific and social contingency plans in place to mitigate the impact on the local population will fail because that population is now too large, and from long tradition underestimates the dangers of an eruption. It would be an excellent starting point for anyone doing SXG390.

Scarth breaks up the text with occasional boxes on subjects that presumably he feels he could not incorporate into the main story, from "The chief types of volcanic eruption" to "His Majesty visibly moved" (Victor Emmanuel III in 1900).

Most of the many black and white photographs are excellent, especially those from 1944, taken by members of 614 Pathfinder squadron, RAF. There are also many useful maps, figures and sketches from old engravings, which would be difficult to understand in their original form. There is a glossary of volcanological terms and a long bibliography.

What the reader will not find is any rigorous geophysics or geochemistry. We have a sketchy account of the local plates and are told in an early box on "The rocks of Campania" that when magma has been in the 'reservoir' a long time on Somma-Vesuvius or Campi Phlegrei it differentiates into trachytes and phonolites, but that is about it. However, it is not that sort of book; and is thoroughly enjoyable and informative as it is.

Alwyn Scarth has already published *La Catastrophe*, an interesting and readable account of Mont Pelée and the destruction of St. Pierre, Martinique, in 1902, which is also in the OUGS library.

— Philip Clark, MA, BSc Hons (Open), Dip Mus (Open)

Magma chamber evolution and large volcanic eruptions

Dr Dan Morgan (School of Earth and Environment, University of Leeds)

Abstract

Large volcanic eruptions are one of the most impressive, and potentially most dangerous, of the natural hazards that humanity faces on Earth. This talk first introduces the Volcanic Explosivity Index (VEI), which is used to describe the magnitude of an eruption, and then looks at a variety of eruption types. This leads on to a description of the problems of mitigating volcanic hazards and some case studies.

During the case studies we will look at the evolution of magma chambers, both in the sense of changing magma composition, and also in the sense of the processes that occur in large magma chambers prior to an eruption.

Measuring the size of a volcanic eruption

The scale of a volcanic eruption can be described using a scale called the Volcanic Explosivity Index (VEI), first put forward by Newhall and Self in 1982. The idea that drives the VEI is simple: volcanic eruptions can be measured in several ways, such as the volume of tephra (fragmentary products) erupted, the height of the eruption column, or the amount of energy released. The VEI is a method by which these different observations can be compared, and used to obtain an objective description of the size of the eruption. Therefore eruptions measured by different groups in different ways can be compared.

A simple figure taken from the United States Geological Survey shows some of the different ways of considering and displaying the VEI (Fig. 1). Most terrestrial volcanic eruptions are of VEI between zero and four, or five. Typically there is an event of magnitude five or six every century or so; Mt. Pinatubo in the Philippines erupted with a VEI of 6.0 in 1991. The Mt. Saint Helens eruption of 1980 was one of the largest and most memorable volcanic eruptions on the US mainland in the 20th century, but had a VEI of only 4.8, less than the VEI 6.0 Katmai eruption that formed the Valley of Ten Thousand Smokes in Alaska in 1912, or the VEI 7.0 the Tambora eruption of 1815.

Types of volcanic eruption

The quietest end of the VEI scale is concerned with events of VEI 0 to 1, which produce very low volumes of tephra. This does not mean that there may not be large amounts of magma involved, but that the magma erupts relatively quietly, without explosive activity. This type of activity is called *effusive activity*, and most lava flows fall into this category; lava flows tend to advance gradually but relatively slowly, and in most cases move more slowly than a person walking. Such low VEI activity, while certainly damaging to property, is usually relatively safe for the neighbouring population. As we increase the VEI, to the range of 1–2, we encounter the phenomenon of fire fountaining, which creates tephra in the form of volcanic bombs, scoria, and rarer products such as Pele's tears or Pele's hair, both formed from the drawing out of magma droplets expelled from a vent on a ballistic path.

Fire fountains typically form at vents where the ascending magma reaches the Earth's surface, and is powered into the air in a jet by a combination of the gas pressure within the magma, and the narrowing of the conduit, in this respect a bit like the narrow nozzle of a hosepipe. Fire fountains can be very short — just a couple of metres high — all the way up to jets 2km high in some of the more extreme cases. The magma fragments as it does so, much like a water-fountain, falling as a rain of droplets and spatter, some of which may form globules the size of a bus. This activity is more violent than quiet effusion, but as it is located close to the volcanic vent it is usually not close to settlements or other human habitation, and so tends to be a very limited threat.

Anything that is of greater violence than the above-mentioned activity is typically referred to as *explosive activity*, and can be due to several different causes, although most are related to the presence of water.

A half-tumbler of liquid water at room temperature will become a cubic metre of steam at 1000°C. Although most magma contains only a small weight fraction of water (0.5–5wt%), even this low amount means that a cubic metre of magma can produce between 60 and 500 cubic metres of steam at normal atmospheric pressure. It is this large steam volume that drives the explosive eruptions, shattering the magma into fragments.

Explosive eruptions can come about in several ways: by the eruption of gas-rich magma, by the collapse of a slowly built-up volcanic dome, or by the interaction of hot magma with ice or liquid water. One of the larger recent explosive eruptions was that of Pinatubo in 1991, which despite being perhaps the joint-largest eruption of the 20th century by VEI, resulted in relatively few casualties despite the proximity to densely inhabited areas.

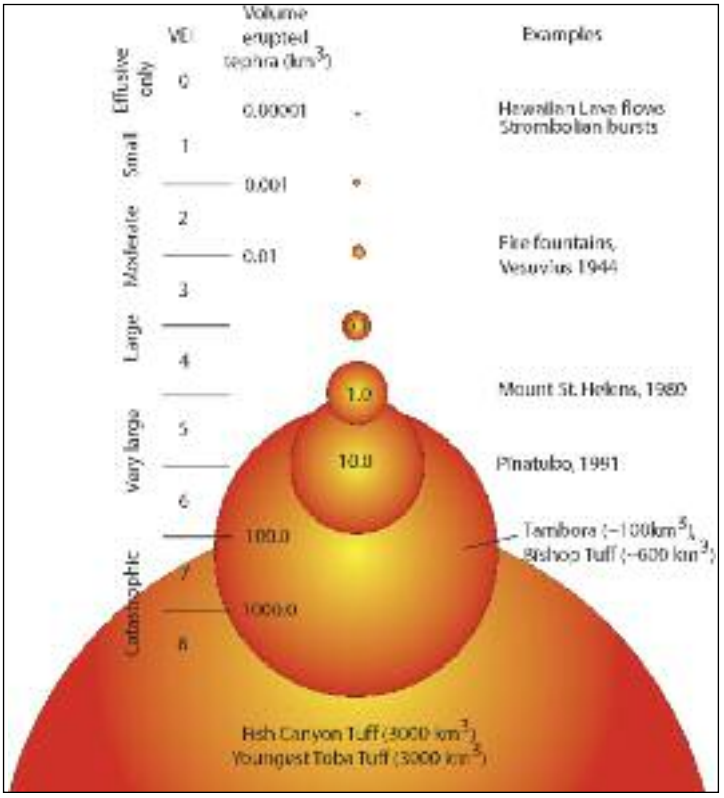

Figure 1 VEI displayed as function of qualitative eruption size and volume of tephra produced; circles give approximations of spheres sized appropriately for relative volume. Eruptions span several orders of magnitude in size, as does the VEI index. Some eruptions are given as examples on the chart (image adapted from one produced by the USGS, http://www.usgs.gov).

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The disaster handling of this eruption is still regarded as one of the best handled cases of its type to date, with more than 1,000,000 people successfully evacuated.

The next stage in increasing VEI is almost exclusively the realm of the *caldera-forming eruptions*. These eruptions involve truly vast volumes of magma, between 10 cubic kilometres and 3,000 cubic kilometres. No simple vent can accommodate the eruption of such large volumes, and calderas are usually driven by the collapse of a thin lid of crust into the top of a magma chamber, which then erupts around the sides of the foundering block. The VEI range associated with caldera-forming eruptions ranges from VEI 6 up to VEI 9, consistent with the range in volumes erupted. Despite the lack of large caldera-forming eruptions during recorded human history, such large events are relatively common in the geological record. For example, the Taupo Ignimbrite of New Zealand, a relatively small eruption of 30km^3 of magma, with a reconstructed VEI of ~6.2, was erupted roughly 1,800 years ago (Fig. 2). The Youngest Toba Tuff, with a magma volume of 3,000km^3 (VEI ~9), was erupted just 74,000 years ago.

To give an example of the scale in human terms, the 27.4 million-year-old Fish Canyon Tuff, (San Juan Volcanic Field, Colorado, USA), is the deposit of one of the largest events known, with 3,000–4,000km^3 of magma erupted. If the products of that eruption were gathered together on the landmass of Britain, they would form a deposit just over 12m deep, from John o'Groats to Land's End, blanketing the entire country and burying almost all housing less than four stories high.

These huge eruptions are not common at a human timescale, but an eruption of the magnitude of Toba or Fish Canyon is still seen roughly once every million years (Fig. 3, *opposite top*). However, the problem is a serious one — the consequences of such an eruption would be absolutely catastrophic for modern society, in terms of the impacts on transport, food production and the global environment, not to mention the devastation caused close to the eruption site itself. But with such a long gap between eruptions, and no historical observations, we have to become very adept at recovering information from the eruption deposits themselves about the conditions prior to and during the eruptions, in order to better understand the dangers posed.

The process of hazard mitigation of volcanic eruptions is a somewhat complex one, but one that it is useful to highlight. In simple terms, there are four groups of people involved in the process (Fig. 4, *opposite bottom*). The scientific effort requires three sets of talents: those of observation and monitoring, which give us information about the volcano's current state; the field and geochemical efforts that tell us about the previous eruptions, and therefore what we may expect from a particular volcano; and the modelling, which takes these two sets of data and attempts to predict what will happen given the volcanic track record and the current monitoring data. The combined results of this past-present-future analysis are used to advise the civil defence authorities, whose job it is to then co-ordinate any response. Contrary to the plot of many disaster movies, it is not the volcanologist who orders the evacuation, but the government; the volcanologist can only advise.

In mitigating the volcanic hazard, we have to answer four questions of increasing difficulty:

1. Where did all the magma come from?
2. What does a magma chamber look like?
3. How long has it sat there?
4. Why did it erupt?

Where does the magma come from?

Ultimately, magmatism at the Earth's surface is the expression of the internal heat of the Earth. The way that the heat is moved from the mantle and into the crust is via the movement of hot, basaltic magma. The movement of a hot basaltic melt is very efficient at carrying heat; the alternative would be a process of

Figure 2 Deposits of the 30km^3 Taupo Ignimbrite (dated at 1,800 years old). The black masses in the deposit are carbonised trees; the area was heavily forested. Interestingly, trees do not have scoria fragments embedded into the wood, suggesting that they were knocked down before the ignimbrite hit them. The idea behind this is that the rapidity of the eruption caused a shockwave strong enough to flatten mature trees of 1m+ diameter.

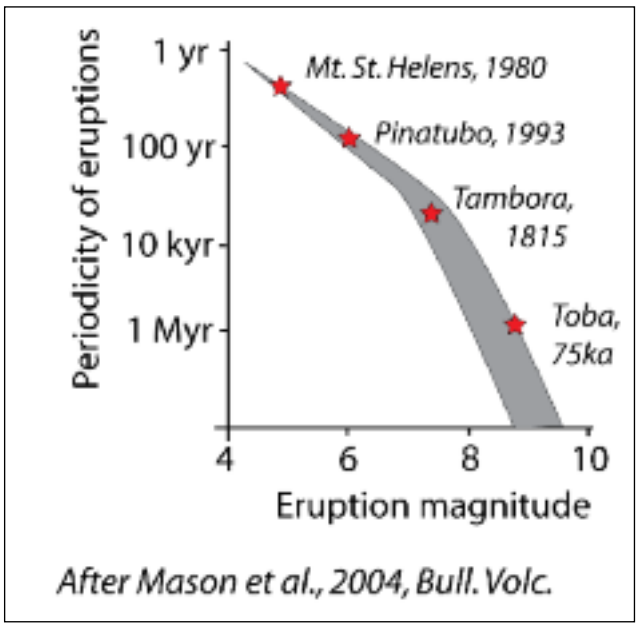


Figure 3 Eruption size versus eruption frequency shows a negative correlation on a log-log plot. Larger eruptions are less common, with something the size of the 1991 Pinatubo eruption expected roughly every century, while major (>1000km³ products) caldera-forming eruptions of VEI 9 are expected roughly once every million years (redrawn from Mason et al. *2004).*

conduction, which over the thickness of the crust is very inefficient and would take millions of years. In the case of large, silicic caldera systems, much of the melt can be generated through crustal melting caused by the intrusion of large volumes of basalt into the lower crust and the subsequent fractionation of that melt to give more silica-rich, evolved magma.

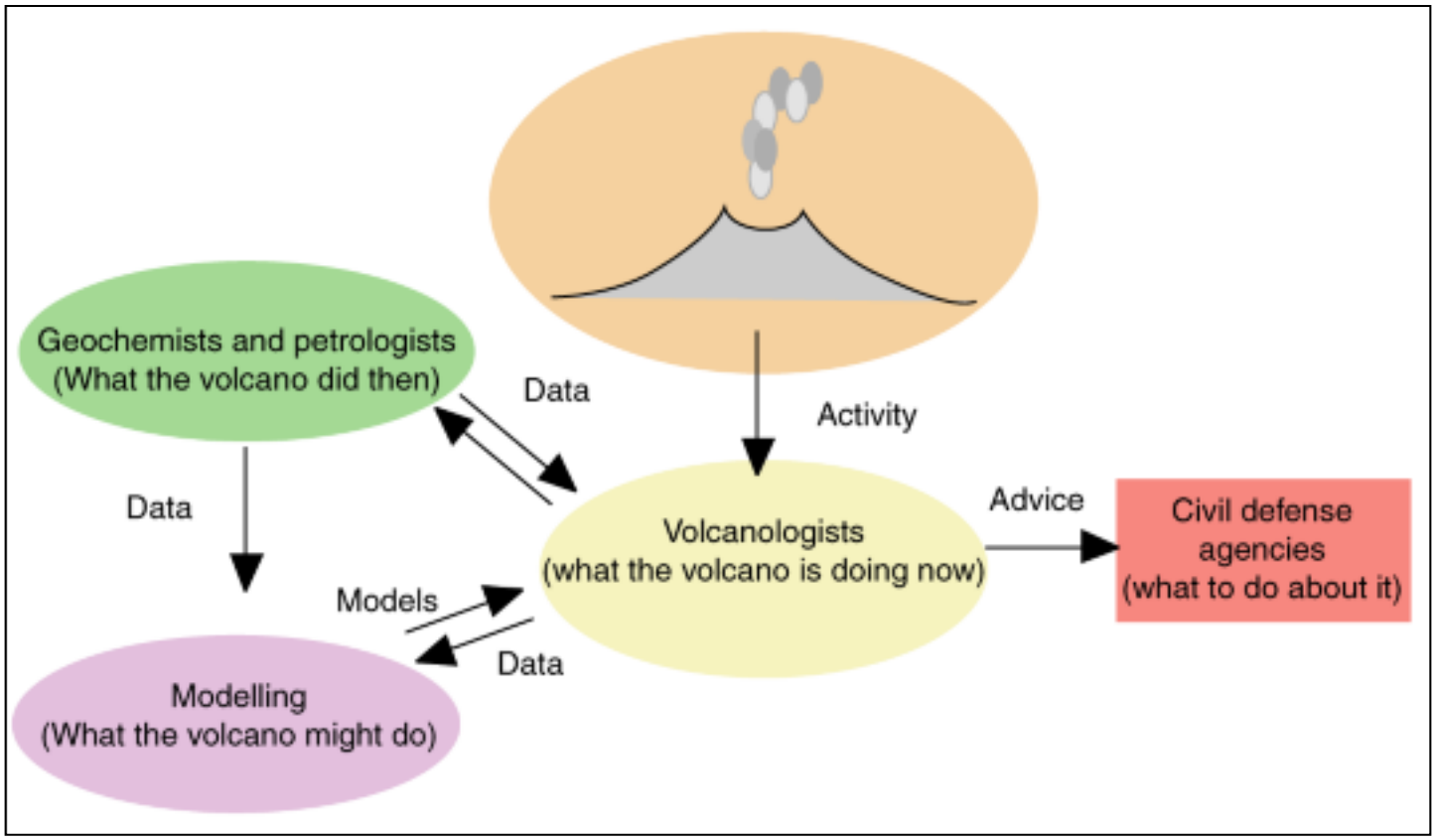
What does a magma chamber look like?

A quick look at the mass balances of volcanic eruptions shows up one glaring fact: the caldera-forming super-eruptions can involve magma volumes of up to 3,000km³, which represents far more, in one event, than the total annual average magma supply of the Earth as a whole. This immediately suggests the need for storage of magmas, in order to build up a large enough volume. This is one of the facts that makes magma chambers a necessary concept.

However, magma chambers themselves have been the source of much speculation and controversy, because no one can really reach a consensus as to what they actually look like, and as to how they behave. The initial idea — taken from a combination of the simple models used to reconcile geophysical data and the observation of large, blob-like plutonic igneous bodies — was that magma chambers are large, blister-like cavities filled with liquid magma. The competing view is that magma chambers are more mush-like, consisting, for the most part, of a fairly solid mush, with a relatively low percentage of liquid magma between crystals — perhaps a bit like a full sugar bowl that has had golden syrup poured into it.

The constraints for this come from geophysical observations. Looking at the ground response as magma chambers inflate and deflate, shows us that there definitely has to be fairly rapid movement of material to create noticeable changes. However, when we look for the seismic signature of the magma, it is hard

Figure 4 Groups involved in volcanic hazard mitigation. Three strands of research, essentially into the current, past and projected future behaviour of a volcano feed into the advice given to the local civil defence agencies.



to find. Liquid magma should be fluid and incapable of transmitting shear waves (S-waves). It would be expected that something as obvious as this would be easy to see; what we find when we look at the seismic data, however, is that while shear waves may be weakened, or *attenuated*, in areas where we suspect magma chambers to be, the S-waves are still present, suggesting that if there is liquid present there is not a large amount, and that some kind of rigid framework is present that enables them to be transmitted.

In this way, the consensus has, after many decades of debate, started to swing towards the mush models of magma chamber structure and away from the earlier liquid filled blister.

How long has it sat there?

How long the magma waits within the crust before eruption is a very important point. If magma accumulates in just 10,000 years, but there is an eruption on average every 60,000 years, that would imply that the magma might sit resident within the crust for 50,000 years, awaiting some undefined trigger to cause an eruption. The way in which we can address this problem is to date crystals from the magmas and see if we can work out how much older they are than the magma in which they were erupted. The problem is that different techniques — often employed on the same crystals — give a range of ages, from tens of thousands of years before an eruption, to as low as ten or a hundred years. So we have a great problem in attempting to understand our data.

One of the ways to explain the discrepancies was put forward by Charlier and Zellmer in the year 2000. They proposed that the crystals are zoned, with old cores and young rims, and depending on what elements you use, the rim or the core will dominate, effectively dating different parts of a crystal.

Once we move to trying to understand our data, we can see that a broadly consistent view starts to appear in the literature. The build-up of magma in one of these systems is prolonged and may take tens of thousands or hundreds of thousands of years. During this time, however, the magma is being affected by short-lived events that affect the crystallisation of the magma and the way that it cools and crystals grow. What we often see with these systems is some kind of re-heating event, of ten years to a few thousand years in duration, which occurs immediately before the eruption. This is known as *magma chamber rejuvenation* and is proposed to both reconcile the long build-up phase and the much shorter pre-eruption timescales that are observed at almost all caldera systems.

Why did it erupt?

The rejuvenation is a key concept in why the magma chambers would be mobilised and subsequently erupt. With a very slow accumulation time, most magma bodies would be mush zones, mostly crystalline. With the addition of significant heat, probably by the intrusion of basalt, the mush breaks down to yield more liquid. The remaining mush can then compact, enabling the crystals to settle and the liquid to rise.

Evidence for this kind of rejuvenation effect is seen from the Fish Canyon Tuff, the Bishop Tuff, New Zealand ignimbrites, and even at smaller systems like Vesuvius or Nea Kameni, Santorini, which respond faster due to their lower volume.

Conclusion

In conclusion, the more that we look for rejuvenation, the more we see these processes going on in volcanic systems at almost all scales. The existence of a liquid-filled magma chamber is at best a very transient phenomenon, caused by the re-heating of large quantities of hot crystal mush. The next step in this research is to determine how quickly these slumbering giants — the caldera systems — can awaken.

References

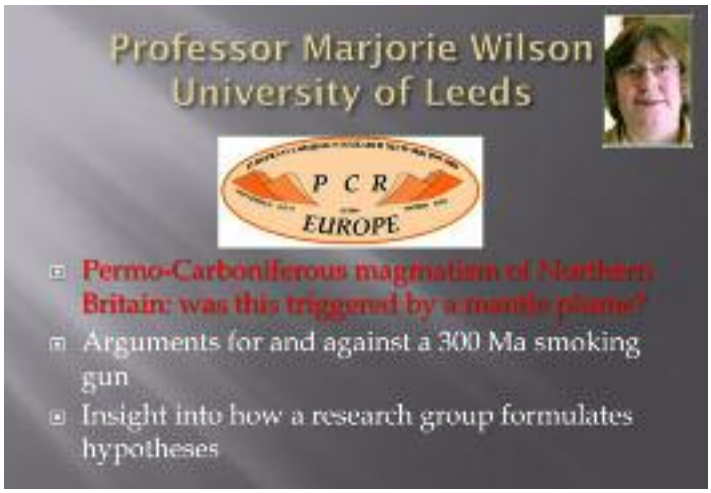
Charlier, B., and Zellmer, G. 2000 ‘Some remarks on U-Th mineral ages from igneous rocks with prolonged crystallisation histories’. *Earth and Planetary Science Letters* **183**, 457–69

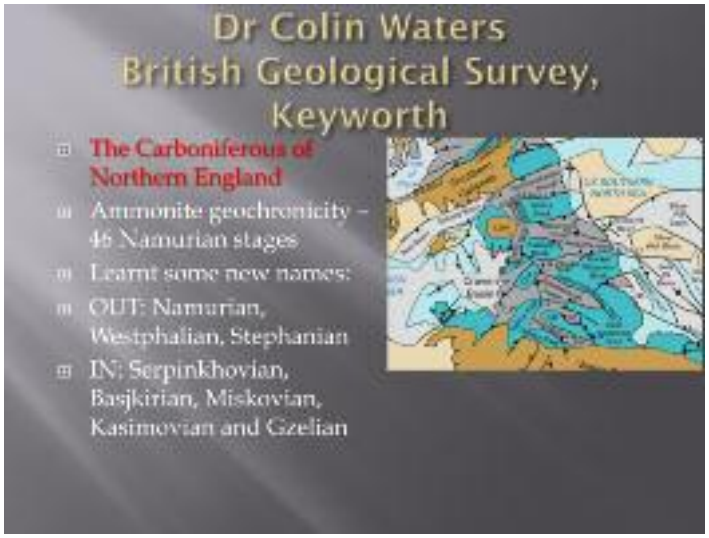
Mason, B. G., Pyle, D. M. and Oppenheimer, C. 2004 ‘The size and frequency of the largest explosive eruptions on Earth’. *Bull Volcanol* **66**, 735–48

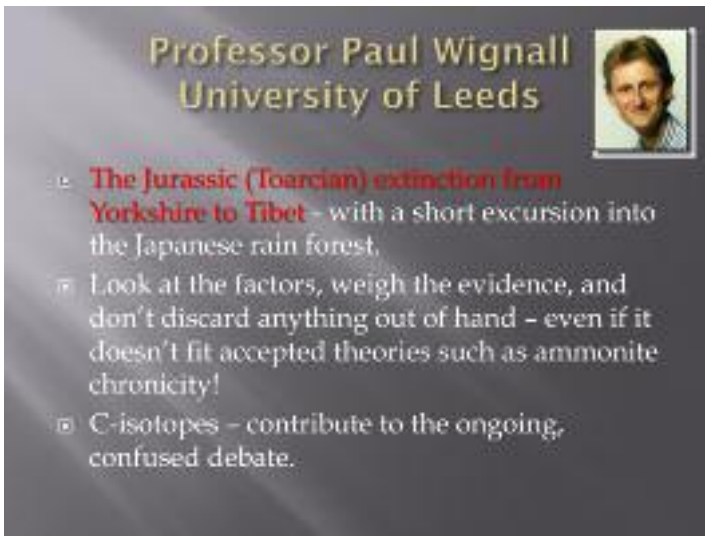
Newhall, C. G., and Self, S. 1982 ‘The Volcanic Explosivity Index (VEI) – an estimate of explosive magnitude for historical volcanism’. *J Geophys Res, Oceans and Atmospheres* **87**, 1231–8

Summary

Chairman Linda Fowler


Professor Marjorie Wilson
University of Leeds
P C R
EUROPE
Permo-Carboniferous magmatism of Northern Britain: was this triggered by a mantle plume?
Arguments for and against a 300 Ma smoking gun
Insight into how a research group formulates hypotheses


Dr Colin Waters
British Geological Survey, Keyworth
The Carboniferous of Northern England
Ammonite geochronicity – 46 Namurian stages
Learnt some new names:
OUT: Namurian, Westphalian, Stephanian
IN: Serpinkhovian, Basjkirian, Miskovian, Kasimovian and Gzelian


Professor Paul Wignall
University of Leeds
The Jurassic (Toarcian) extinction from Yorkshire to Tibet – with a short excursion into the Japanese rain forest.
Look at the factors, weigh the evidence, and don't discard anything out of hand – even if it doesn't fit accepted theories such as ammonite chronicity!
C-isotopes – contribute to the ongoing, confused debate.

Dr Mike Romano
Sheffield University
Dinosaur footprints on the Yorkshire coast
Working with Mark White and Earthwatch International, and the Sheffield Dinosaur Footprint Research Group
Ammonites give the dates
When does a morphotype become an ichnospecies?
What is dinoturbation?

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Environment

Dr Mark Bateman
University of Sheffield

- The ebb and flow of the Yorkshire margins of the last British icesheet
- Skipsea till erratics of rhomb porphyry and larvikite from Olso graben
- Lake Humber 16.5ka – size? Beach level? Humber blocked
- One advance? 2 advances? Ice streams – fast ice and dynamic ice margins
- Next ice age overdue

Dr Alan Haywood
University of Leeds

- Palaeoclimate modelling: the past as a guide to the future
- More important than Jamaican coffee and lie-in!
- Occam's razor; Furry alligator syndrome.
- Greenhouse to icehouse transitions
- Climate sensitivity or Earth system sensitivity?
- The different world of the mid-Pliocene informs current debate
- Identify contribution from different components: CO_2 is king and total of components on Earth System Sensitivity basis is 5°C

Dr Mark Williams
University of Leicester
(and Dr Jan Zalasiewicz, BGS Keyworth)

- Are we now living in the Anthropocene?
- A new epoch (or period, or even era): have we fundamentally altered Earth system, when, and how?
- Possibilities for an Anthropocene boundary golden spike:
- Not human influenced diachronous boundaries.
- What about metalworking? Oldest cities? Agriculture? Stone tools? Steam engine? Terraforming ... Globally ischronous concrete surface? 1940s atom bomb tests, or Chernobyl: global sediment signatures? Coincident natural event e.g. Tambora? CO_2?
- Is the boundary in the future?

HOT ROCKS

Dr Dave McGarvie
The Open University

- Volcano-ice interactions in Iceland
- Video footage of eruptions
- 6-person sleeping bags
- Eruptions under ice and through thin ice; flows over ice; dome eruptions
- Effects when lava and water or ice meet
- Ice confined eruption: **tuya**.
- Recent research on rhyolite subglacial eruptions
- Comparison of 2 historic eruptions of Oraefjökull 1362 (rhyolite) and 1727 (basalt)
- Current field work – rhyolite, columns, perched and ridge forming lavas – give ice thickness data

Dr Dan Morgan
University of Leeds

- Magma chamber evolution and timing of large volcanic eruptions
- Vesuvius: understand hazard to mitigate future risk
- Bimodal products: tephrite and phonolite (less / more explosive). Violence/time scale correlation.
- Increasing Ba concentration / mobility in sanidine crystals = key to events e.g. recharge of magma chamber, preceding eruptions. 100 year fuse!
- Caldera: piston effect – efficient, rapid draining of magma chamber. E.g. Taupo, Bishop Tuff, Fish Canyon Tuff
- Common factor: rejuvenation of mush by input of heat leads to remobilisation of magma and eruption

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